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Environmental and Socio-Economic Impacts of the Circular Economy Transition in the EU Cement and Concrete Sector

Analysing cement and concrete material flows with life cycle-based and macroeconomic assessment models

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Contents

Abstract

In the face of accelerating climate change and a shifting geopolitical landscape, the circular economy (CE) paradigm is emerging as a critical strategy in EU policymaking. It is of particular importance for the cement and concrete sector, which accounts for about 4% of EU greenhouse gas (GHG) emissions. This study demonstrates that implementing CE levers related to reduction, reuse and recovery could significantly reduce GHG emissions by 38-52 Mt CO_2-eq. annually by 2050, in addition to savings from energy decarbonisation measures. Moreover, CE levers are projected to enhance the EU's trade balance by approximately EUR 6.1 billion annually by 2050, due to decreased imports. However, potential trade-offs from CE levers related reduction and reuse, such as slightly lower employment and economic growth, necessitate further research into socioeconomic impacts in service sectors. Key CE levers include substituting clinker with alternative binders, reducing the use of concrete by design, as well as advancing cement fines recycling technologies. The findings underscore the necessity for a comprehensive policy mix to harness CE's full potential, with a focus on the production and use phase, given the large material flows in the construction versus the demolition phase. Therefore, economic incentives related to financial support of clinker alternatives and novel types of cement, as well as cement recycling technologies are proposed. Moreover, policy measures could feature the inclusion of novel cements in green public procurement award criteria, in addition to updating cement, concrete and building standards towards performance-based standards. In the light of the forthcoming Circular Economy Act in 2026, this research provides detailed insights for policymakers to implement CE measures that go beyond waste legislation to ensure a resilient and competitive EU industrial sector.

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Executive summary

Within a rapidly shifting geopolitical landscape and climate change advancing at a pace that outstrips global efforts to mitigate its causes, the circular economy (CE) paradigm is gaining momentum in European Union (EU) policymaking. As part of the highest emitting sectors in the EU, contributing about 4% of the EU greenhouse gas (GHG) emissions, the cement and concrete sector has been under particular scrutiny. This study analyses how the increased implementation of CE principles can alleviate some of the decarbonisation pressure on the sector and make the net-zero target by 2050 more attainable, with more efficient use of resources and rerouting of material flows. By applying a multi-method research design, the cement and concrete sector is analysed from different perspectives and the results synthesised into recommendations for policy makers. Beyond policy makers, the developed models and data created are also meant to be of value for scientists and consultants who aim to quantify the environmental and socio-economic effects of CE in the cement and concrete sector.

Policy context

The EU's Green Deal in 2020 solidified CE as a crucial component of the EU's strategy to achieve climate neutrality by 2050. It was followed by the EU Competitiveness Compass, published in January 2025, which highlights the role of CE in promoting more prudent resource use and increased recycling. Moreover, the Clean Industrial Deal, subsequently published in February 2025, emphasises the importance of CE in creating a sustainable, resilient, and competitive European industrial sector, with a focus on promoting clean circular technologies and job creation. To this end, the upcoming Circular Economy Act, set to be released in 2026, will aim to promote recycling capacities, encourage the use of secondary materials and reduce the EU's reliance on imported virgin resources. While current CE policy does not directly include targets related to climate action or competitiveness in the cement and concrete sector, its contribution in both can be substantial, especially in terms of lowering costs to achieve climate targets by more efficient energy and material use. For a better understanding of potential points of policy interventions in the cement and concrete life cycle, it is crucial to identify the environmental and socio-economic impacts of CE strategies, such as reduction, reuse and recovery.

Key conclusions

The implementation of CE in the EU cement and concrete sector can lead to significant environmental benefits, including reductions in GHG emissions, energy and resource consumption, and waste generation. These reductions are mainly due to the decrease in cement and concrete demand, given the high material inflows from construction, versus the outflow from demolition. Therefore, CE strategies at the start of the lifecycle are more effective than at the end of the lifecycle, given the high difference of magnitude of the material flows. In terms of effects on trade, which is less strategic than, for instance, for the metal sectors, CE implementation entails a reduction of cement imports alongside decreases in demand for fossil fuels coming from outside the EU. This leads to an increase in the EU trade balance with its global trade partners. However, the study also hints towards trade-offs in terms of slightly reduced employment and gross value added compared to a future without CE measures. However, additional research is strongly encouraged to better understand the CE consequences in the service sectors, which were not in the focus of this study. Overall, the economy is still projected to grow, but at a slightly slower pace than without CE implementation, while GHG emissions are decreased substantially, thus leading to a decoupling effect.

To unlock the potential of CE, a holistic life cycle approach, careful policy design, and coordination among stakeholders are required. In this sense, the study emphasises the importance of a policy mix approach, combining different policy instruments to address the multiple challenges of a potential CE transition in the EU, including a wide range of administrative, economic, and informative instruments, both of mandatory and voluntary nature. While past CE policy mainly focused on the end-of-life phase, this study makes the case that policy affecting the production and use phase is just as, if not more, effective. The proposed policy measures primarily take shape of price-based or performance-based economic incentives (e.g. financial support to clinker alternatives and recycling of construction and demolition waste to cement fines, or green public procurement requirements, respectively). Moreover, the advancement of updating cement, concrete and building standards towards performance-based standards in member states is also of high priority.

Main findings

- The implementation of CE levers can achieve an additional impact reduction on climate change of 38-52 Mt CO_2-eq. annually by 2050, on top of decarbonisation measures. Reduction levers contribute the largest share of this reduction, of about 29 Mt CO_2-eq., given the material flow structure of the sector.
- CE can lead to a decrease of about 52 petajoules of the EU demand for fossil resources and a decrease of 18 terawatt hours of electricity. Given the goal of 95% energy from co-processing of bio and waste fuels in the cement sector, CE implementation can lead to energy savings of 41% for biomass, 37% for electricity, 27% for natural gas and 20-22% for in crude oil and coal.
- The decrease in resource and energy demand for the cement and concrete sector can lead to a trade balance increase of ca. EUR 6.1 billion annually for the EU, due to reduction of imports from China, the US, UK, and Russia.
- CE strategies related to absolute reduction without substitution with other products may lead to lower growth projections in Gross Value Added and employment, highlighting the need for further research on the CE implications on service sectors.
- Key CE levers include:
    - Substitution of clinker/cement with clinker alternatives and alternative binders, given their availability and high technology readiness. Though initial investment for retrofitting cement plants is necessary, it enables GHG reduction at a lower price than carbon capture and storage.
    - Reduction of concrete use by reducing the overspecification in standards and using the material more economically. In contrast to previous findings, the replacement of concrete with wood should be based on local material availability, as it does not entail significant GHG savings and potentially increases production costs significantly.
    - Reuse of structural and pre-cast concrete elements is to be facilitated by clarifying questions of insurance and safety considerations, which are frequently the most important barriers impeding reuse.
    - Recycling of concrete waste to recycled cement fines should be further developed and scaled up, given they bear a GHG savings potential 20 times higher than recycling to recycled aggregates only.

Related and future JRC work

Relevant JRC studies that have laid the background for the data and development of the assessment methods for the material flow analysis and life cycle assessments include studies on modelling the cement and concrete material flows in the European Union value chain (Cristóbal García et al., 2024; Damgaard et al., 2022), a study on the emissions of cement and the construction sector more in general (Marmier, 2023), as well as studies study on environmental and economic assessments of construction and demolition waste (Caro et al., 2024; Pristerà et al., 2024). The work related to the macro-economic modelling is based on the FIGAROe3 tables (Cazcarro et al., 2025) and the FIDELIO model (Rocchi et al., 2025).

The priority of future work should be on better capturing the socio-economic effects of reduction and reuse levers in the macro-economic models. This is essential to induce and manage demand reduction in an equitable and economically competitive way.

1 Introduction to the cement and concrete sector in the EU

The production of cement and directly related thereto, concrete, are amongst the most used materials in the European Union and globally, in terms of mass flows. Whereas concrete is prominent in terms of volumes, the cement sector has been under particular scrutiny due to the greenhouse gas emissions emitted during cement production. The 4.1 Gigatonnes of cement produced globally accounted for about 1.6 billion tonnes of CO_2, making up ca. 8% of the total CO_2 emissions (Friedlingstein et al., 2023). The production share of the EU is a mere 4.3% of these, amounting to 171 million tonnes (Mt) and about 4% of the total CO_2, in the EU (Cavalett et al., 2024; CEMBUREAU, 2024a). In the light of European Climate law however, directing the continent towards becoming climate-neutral by 2050, cement is becoming a key sector to decarbonise. These emissions are considered hard-to-abate, as the material itself, the connected industry, construction, as well as the end products, buildings and infrastructure are essential for civilisation in its current and future state (Habert et al., 2020). Therefore, significant investment in novel technologies are advocated for by industry actors to steer the cement sector towards lowering their emissions along the entire cement life cycle (IEA and WBCSD, 2018; International Energy Agency, 2023). The strong focus on climate mitigation might explain why the other emissions from concrete production, mainly related to human health, have not been attributed equal attention. Miller & Moore (2020) report that concrete production is responsible for about 8% of nitrogen oxide mission, 5% of sulphur oxide emissions, as well as 5% and 6% of particulate matter emissions smaller than 10 and 2.5 microns respectively. These non-GHG emissions are mainly caused by the production of aggregates, with a more local scope of impact.

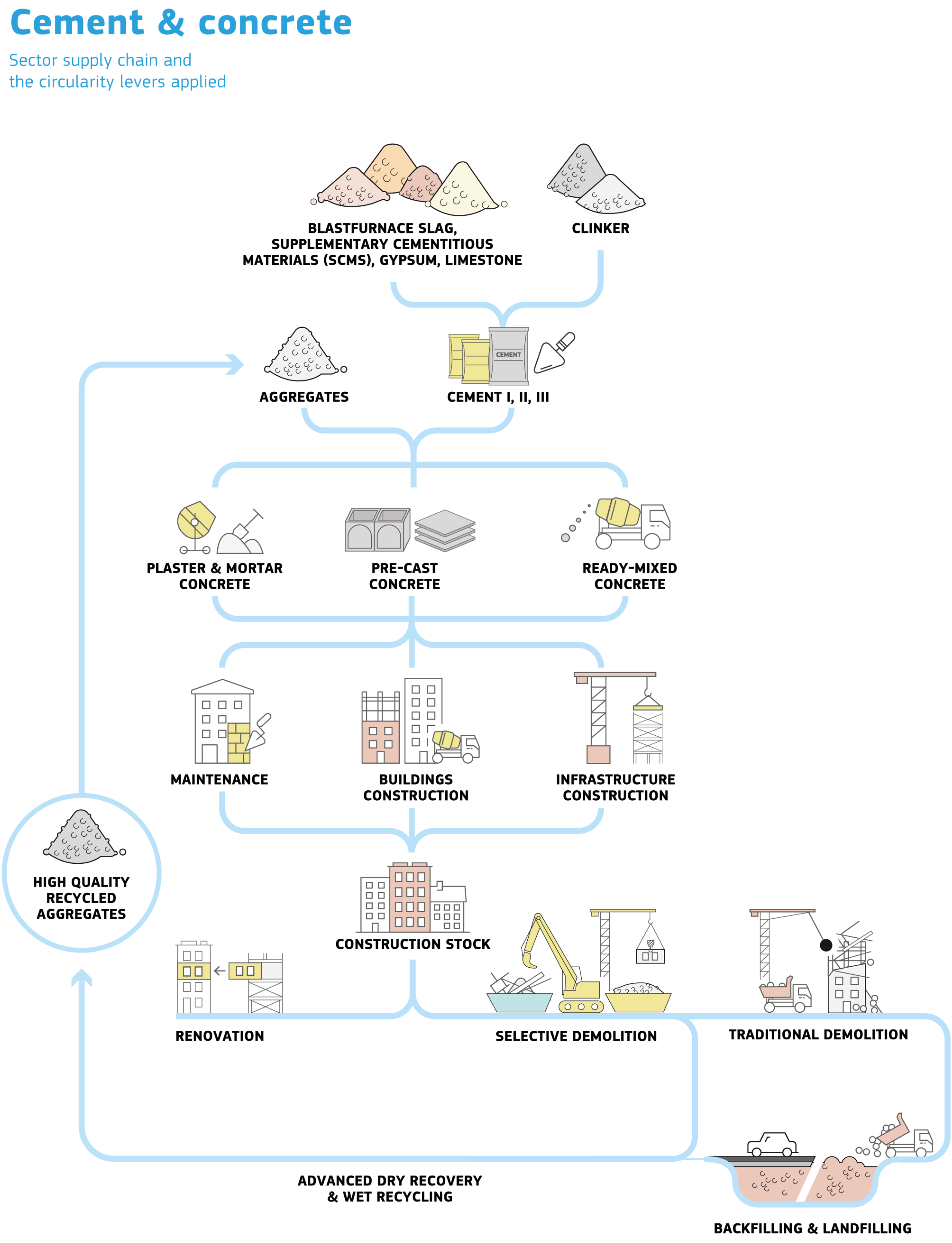
In attempt to limit the these impacts, the concept of circular economy (CE) has frequently been brought forward, particularly in connection with GHG emission reduction (Fraunhofer ISI & European Commission, 2023; Material Economics, 2018; Zibell et al., 2022). With a lifecycle perspective, the CE allows for analysing the material flows from the raw materials through production, use phase and end of life, with the ultimate goal of closing the material loop. In this context, the construction sector, being the largest material user and waste generator in terms of mass, exhibits certain peculiarities to be taken into account when implementing CE actions such as reducing, reusing and recovering material. These include, amongst others, the long lifetime of buildings and the (to date) limited recyclability of concrete, making up the majority of construction and demolition waste (Ossio et al., 2023). For a better understanding of potential points of policy interventions in the cement and concrete life cycle, it is crucial to identify the environmental and socio-economic impacts of CE strategies, such as reduction, reuse and recovery. This report presents a multi-method analysis of potential CE strategies to be implemented in the EU by 2050. The material life cycle is captured with a material flow analysis (MFA), and the environmental impacts thereof identified through a life cycle assessment (LCA) and life cycle costing (LCC). This bottom-up perspective is complemented by an environmentally extended input output analysis as well as macro-economic modelling to capture the potential economy-wide rebound effects. Before diving deeper into the research design, the material system is described in the following section. Thereafter, current and future trends in cement and concrete production are outlined and the socio-economic importance of the sector described. The introduction ends with a description of the most pressing challenges the sector is facing both in the current industry and policy landscape.

1.1 The life cycle of cement and concrete

An overview of the life cycle of cement and concrete is presented in **Figure 1**. The raw materials of cement mainly consist of clinker and supplementary cementitious materials (SCMs) such as blast furnace slag from steel production, fly ash or natural pozzolans. The global clinker rate in cement is 71% (International Energy Agency, 2023), whereas this average is slightly higher in Europe, at 77% (CEMBUREAU, 2024a). The composition of the cement depends on the region, but it is expected that by 2050, the clinker rate will be at 60%, the remaining supplementary cementitious materials being calcined clay (8%), blast furnace steel slag (7%), fly ash (1%), lime stone (18%), natural pozzolana (2%) and gypsum (4%) (IEA and WBCSD, 2018). The share of SCMs from by-products of production processes relying on fossil fuels, such as blast furnace slag or fly ash are expected to decrease significantly from today's levels, due to the phase out of these technologies (UN Environment et al., 2018). The clinker production is the most environmentally impactful production step, emitting between 832 to 1,075 kg CO_2-equivalents per tonne (Cavalett et al., 2024; A. Müller et al., 2024). As limestone is calcinated into calcium oxide, about 60% of the CO_2 emissions are emitted, while being mixed with clay and calcareous marl or quartz. The remaining 40% of the emissions are due to the combustion of fossil fuels and alternative fuels for heat production. Whereas traditional fossil fuels such as natural gas, coal and pet coke currently make up 48% of the fuel mix, the remaining 52% are composed of biomass waste (17%) and non-recyclable waste (35%) such as used tires, refuse derived fuel (RDF) and municipal solid waste (CEMBUREAU, 2022). The share of alternative fuel in the so-called co-processing is expected to increase up to 95%, according to industry (CEMBUREAU, 2024b). After the cooling and addition of the aforementioned SCMs, the cement is mixed with aggregates, consisting of sand and gravel, as well as water and additives to different types of concrete.

These are either ready-mixed concrete (56%) to be casted immediately at the construction site, pre-cast concrete (18%) casted in the factory before transport, and plasters and mortars (26%), directly mixed with water on site. The concrete is used for construction of buildings and infrastructure, as well as maintenance activities, whereafter the structure is in use for long live span, that can range between 50 to over 100 years. During that time, the structure is potentially renovated or reused for other purposes, though that does not significantly affect the material flow of concrete directly. In the case of renovation, complementary material flow such as tiles, glass and ceramic are more prominent (Damgaard et al., 2022). The end of life happens through either traditional or selective demolition, the latter enabling a more careful separation of materials for reuse and recycling (Luciano et al., 2022). Whereas some structural elements can potentially directly be reused on site, waste concrete can be recycled into recycled concrete aggregates, replacing gravel or sand (Pacheco et al., 2023). More recently, several research projects have also assessed the option of further recycling cement fines into SCMs for cement and raw materials for clinker (Moreno-Juez et al., 2020; Zhang, Hu, Dong, Gebremariam, Mirand-Xicotencatl, et al., 2019). However, this technology is not yet at scale and a significant share (13%) of concrete waste continues to be landfilled, preventing the material from recirculation into the economy (Cristóbal García et al., 2024).

Figure 1. Life cycle of materials containing cement



Source: Adapted from Habert et al. (2020)

1.2 Production figures and trends

In 2022, China accounted for more than half of the global concrete production, whereas the EU27 made up a mere 4.3% of the production (CEMBUREAU, 2022). The second largest producer is India with 9%. It is expected that the majority of cement and concrete will be produced in the Global

South by 2050, with especially Southeast Asian and African countries showing high growth rates (Cheng et al., 2023; *GNR 2.0 - GCCA in Numbers : GCCA*, n.d.). Whereas global demand of cement is projected to supersede 2020 levels by 12-23%, the production in Europe is estimated to plateau after 2030 (S. Deetman et al., 2020; Material Economics, 2019; Nilsson et al., 2020). This decline has been initiated by the 2008 real estate crisis, and is complemented with a shift from new construction to renovation, which already accounts for 42% of turnover in the building market (CEMBUREAU, 2024a). It needs to be underlined that the costs of concrete and mortar usually only make up about 10 % of the total project costs, thus making it impossible to use the sector's turnover as a proxy for material use (Watari et al., 2022). Indeed, cement consumption is mainly feeding new buildings (42%), building renovation at 4%, new civil engineering structures (25%), renovation of civil engineering structures (1%) as well as 28% that are unaccounted for (CEMBUREAU, 2022). While essential to the citizens in Europe, the cement and concrete sector are highly localised industries with limited trade. This is mainly due to the weight of the material as well as the wide availability of raw materials in the earth's crust (Habert et al., 2020). Net export of clinker and cement is currently at about 2 Mt per year with the main export partners being the UK and United States, whereas the imports mainly come from Turkey and Algeria (CEMBUREAU, 2022). For concrete, the value are even lower and similarly for aggregates. Therefore, the competitiveness of the cement and concrete is not as strategic as in other sectors, which are more dependent on trade (Marmier, 2023).

According to CEMBUREAU (2024b), the cement sector in the EU27 currently directly employs 350,000 Full Time Equivalents (FTEs) and about 200 integrated cement plants are operating in Europe. The sector directly connected to it, are the ready-mixed concrete, pre-cast concrete, mortar and aggregates sector, which are supplying the construction sector. The cement and concrete sector had a joint turnover of EUR 92.8 billion in 2021. In 2019, there were 11,463 ready-mixed concrete plants in the EU27, and member companies of the European Ready Mixed Concrete Organisation, representing 66.5% of the production volume, had a turnover of 11.4 billion EUR, employing about 45000 FTEs directly (European Ready Mixed Concrete Organisation, 2020). In 2022, the precast concrete sector, including EU27, EFTA and UK had a turnover of about EUR 36 billion, employing around 160,000 FTEs with 8,000 manufacturing plants owned by 5,000 companies. The aggregates sector, with its annual turnover between EUR 25-20 billion and 3 billion metric tonnes of aggregates per year supplies about 45% of these aggregates to concrete and employs 187,000 FTEs in 15,000 companies across 26,000 sites (Aggregates Europe, 2022).

1.3 Policy landscape for decarbonisation

The decarbonisation of the EU industrial sector is guided by the Commission's 2020 Industrial Strategy and the updated Industrial Emissions Directive in particular. Market incentives through carbon pricing, an emission trading system (ETS) and carbon border adjustment mechanisms (CBAM) were established to promote the employment of low-carbon technologies (Sartor et al., n.d.). As the free allowances for emissions for the cement sector are to be phased out by 2030, the negative economic effect thereof is to be counterbalanced by the CBAM to counter carbon leakage (International Energy Agency, 2023). The International Carbon Action Partnership reports the development of 36 ETS systems at different administrative levels, reaching from cities, provinces and states to countries and the supranational level (the EU+EEA) (ICAP, 2024). It remains to be seen if these carbon pricing and market protection instruments are compatible with increased investment in more climate-neutral technologies, given the cement sectors historical low innovation potential (Dewald & Achternbosch, 2016; Marmier, 2023). The highest level of innovation is observed in Japan and Germany, followed by France. Scholars have found that material use optimisations linked to CE practices across the supply chain can reduce the CO_2 emission by up to 50% in the traditionally rather sluggish and risk-averse industry (Habert et al., 2020; Watari et al., 2022). However, European companies are currently investing significantly in carbon capture and storage (CCS), where Japan is tailgating them (European Commission, 2021).

CCS is seen as unavoidable by the cement industry due to the process emissions, so even if the energy were to be carbon neutral, calcination would still emit CO_2 (ETC, 2022). Therefore, CCS is estimated to account for capturing about 57% of the CO_2, supporting the goal of net zero-emissions by 2050 (CEMBUREAU, 2024b). Industry is predicting that CCS will be deployed in up to 85% of cement producing facilities globally. The achievement of this roll-out is currently off-target, given the insufficient inflow of investment into the technologies (ETC, 2022). Though there are several pilot projects running or under construction, scholars more cautiously assume that by 2050 no more than 25% of the production capacity in the EU27 will be equipped with CCS systems (Cavalett et al., 2024). Notwithstanding the importance of CCS in the long run, i.e. beyond 2050, investment into upscaling of existing technologies independently of CCS are thus seen just as crucial for achieving the net zero emissions target (Favier et al., 2018; Georgiades et al., 2023; A. Müller et al., 2024).

1.4 Report structure

The report is structured into seven more sections. Section 2 is lining out how the concept of the CE can support more efficient management of material flows in the cement and concrete sector, followed by a description of future scenarios to be analysed. Thereafter, the bottom-up perspective of the assessment is divided into Section 3, sketching the material flow analysis and Section 4, describing the life cycle assessment and costing. The top-down perspective is enabled through an environmentally extended input output analysis laid out in Section 5 and dynamic modelling to capture socio-economic rebound effects in Section 6. A discussion in Section 7 synthesises the results from the different parts and infers their implications for policy makers. Finally, Section 8 concludes the study with a summary and further research avenues.

2 Circular economy scenarios for the future

The research design of this study is composed of several components. First, the circular economy (CE) clusters are introduced to streamline different types of circularity for the analysis. In a second step, two scenarios are explored against the current status quo; one, which simulates the absence of CE clusters and another, which aims to maximise the material savings and minimise the negative environmental impact. These two scenarios are then assessed with the methodologies proposed in the following chapters.

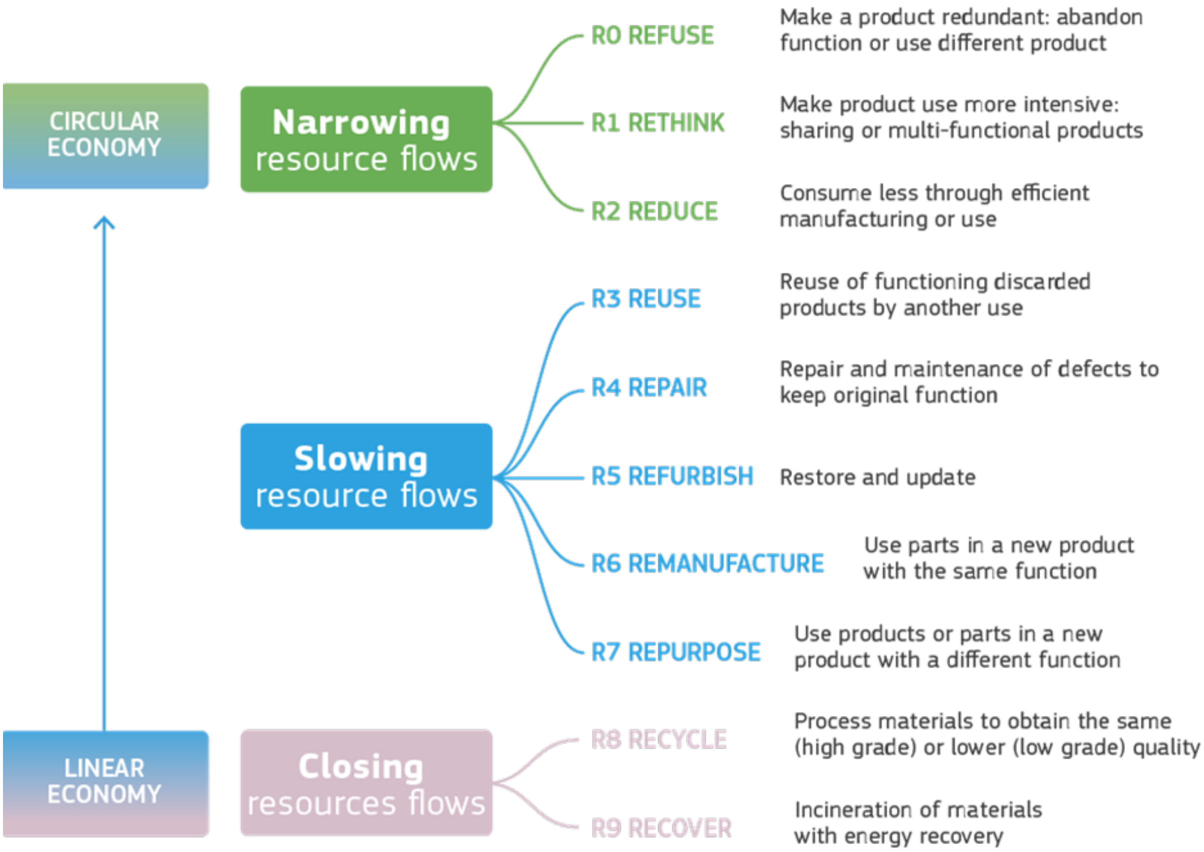
2.1 Circular economy strategy clusters

The concept of CE has proliferated over the last decade, especially after the introduction of the first CE Action Plan for Europe published by the European Commission in 2015. Although there is no single definition for CE, it is generally understood as an economy where the value of materials is maximised and maintained for as long as possible. Moreover, the input of materials and their consumption is minimised, the generation of waste is prevented and negative environmental impacts reduced throughout the life cycle of materials (OECD, 2024). The recently published ISO 59004 Circular economy standard (2024) defines CE as an '*economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development.*'

This is to show that the concept of CE is multi-dimensional (Ghisellini et al., 2016) and relates to other concepts, including but not limited to, the so-called R-framework that distinguishes different strategies to achieve the goals of circularity, the concept of resource productivity or resource efficiency, and sustainable materials management. Though there are several types of classification of CE (Calisto Friant et al., 2020), the more techno-centric narrative used in this report has the objective of reducing natural resource extraction and decreasing environmental and social impacts, while limiting the associated reduction of economic output. In line with this argumentation, the implementation of CE strategies not only facilitates the sustainability transition, but also contributes to increased competitiveness, job creation and re-industrialisation (OECD, 2024).

CE strategies take place at different levels, including different governance levels (regional, national, supra-national), different firm/sector levels and different geographical areas. The most common approach to identifying and defining CE strategies is the 'R Framework' (Reike et al., 2018). The number of 'R's featured in the R Framework has evolved over time, from the Japanese Government's '3R Initiative' (reduce, reuse, recycle) in 2004, to the European Union's waste hierarchy in its 2008 Waste Framework Directive featuring four Rs (reduce, reuse, recycle, recover), to ten Rs which constitute the 2017 "Circularity Ladder" (Potting et al., 2017), illustrated in **Figure 2**.

Figure 2. Overview of CE strategies, separated into narrowing, slowing and closing resource flows



Source: Based on Potting et al. (2017)

The R-Framework is useful in presenting a whole array of CE strategies aiming at a certain material flow outcome, specified as (i) reduction of material input, (ii) extension of material useful life, and (iii) recirculation of materials at the end of life of products. The specific CE strategies exemplify the different ways to achieve similar material flow outcomes, by diverse operations. For instance, the R-strategies 'Reuse', 'Repair', and 'Refurbish', all constitute distinct ways of extending the lifetime of products; yet, their final outcome with regards to material use is the same. Therefore, the R-framework can be simplified into a resource outcome-oriented R-framework that puts forward the broad categories of "Reduce", "Reuse", and "Recover" as the primary clusters. Similarly, research on CE strategies concurs on the usefulness and applicability of this approach, especially when taking a business or policy perspective (OECD, 2024). For instance, Bocken et al. (2016) have introduced the 'narrowing, 'slowing', and 'closing' resource loops approach, corresponding to the aforementioned 'reduce', 'reuse' and 'recover' clusters of R-strategies. A more detailed description of the three clusters is presented below:

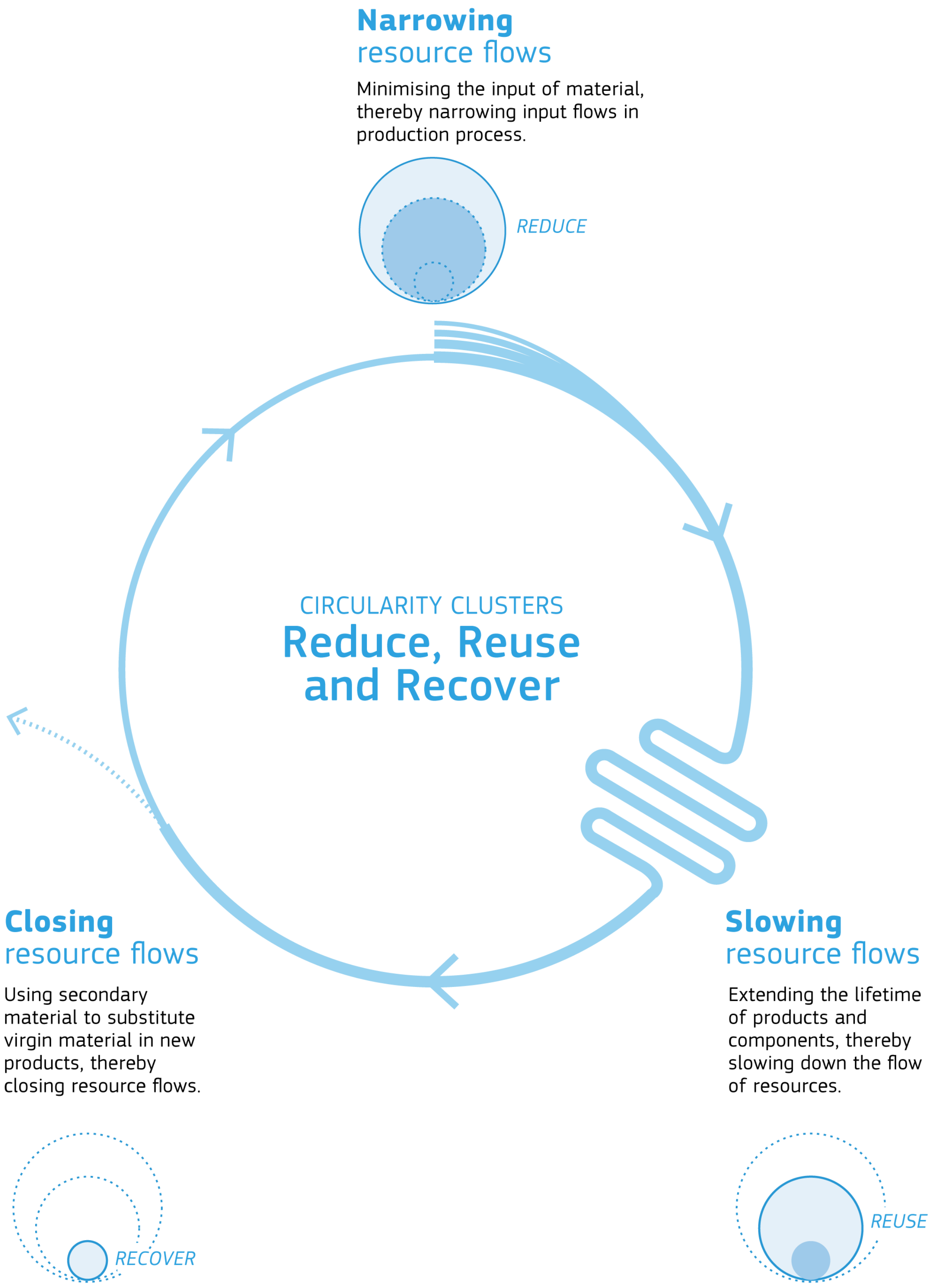
- Reduce: Narrowing resource loops and flows increases resource efficiency, either by decreasing the total amount of resources used per unit of output or by making more economic use of existing production capacity, and using natural resources, materials, and products more efficiently. This could be achieved either through the development and diffusion of new production technologies, the increased utilisation of existing assets, or shifts in consumption behaviour away from material intensive goods and services.
- Reuse: Slowing resource loops reduces the need for additional consumption and demand for primary raw materials by extending the lifetime of existing goods. This can be achieved

by e.g. building long-lasting products that are easy to repair and the ownership of which can change during their lifecycle.

- Recover: Closing resource loops prevents waste from being generated by reprocessing materials that have reached their end of use stage and re-introducing them into new products as secondary raw materials, thus substituting demand for primary raw materials in production.

Furthermore, each of the R-strategies can be applied in isolation or in connection with another, according to anticipated outcomes. There is a certain dependency of the CE clusters in relation to their application, with the ‘Reduce’ cluster affecting also the outcomes of the remaining CE clusters, as illustrated in **Figure 3**. Since, on the one hand, in a ‘narrow’ resource loop – at the beginning of a product’s life-cycle – the volume of material is defined, only that amount can become available for the application of the remaining CE clusters (i.e. slowing or closing loops). On the other hand, closing resource loops and reclaiming secondary raw materials can also have an effect on reducing the demand of primary raw materials.

Figure 3. Conceptualisation of circularity clusters into *Reduce*, *Reuse* and *Recover*



Source: Adapted from Konietzko et al. (2020); OECD (2024)

In conclusion, taking stock of the available knowledge on the definition of CE and respective R-strategies commonly applied, in this study we consider the following CE clusters:

- **Reduce resource input** (corresponding to R0-R2 and the 'narrowing' resource loop strategies) → REDUCE
- **Slow resource throughput** (corresponding to R3-R7 and the 'slowing' resource loop strategies) → REUSE
- **Enhance resource recirculation** (corresponding to R8 and the 'closing' resource loop strategies) → RECOVER

From the CE cluster framework applied in this study, the energy recovery from resources is explicitly excluded, since the focus is on material resource circularity. Once materials go through an energy recovery process, they cannot be reused in any physical operation, neither as secondary material inputs nor as spare parts/components, and therefore are exiting the economic system.

2.2 Scenarios definition

To quantify the environmental and socio-economic impacts related to different CE clusters, a status quo reflecting today's situation and two[1] different scenarios future scenarios in 2050 are defined as follows:

- **Status Quo scenario (STQ20)**, reflecting current conditions (i.e. with 2020-2023 data).
- **Baseline scenario (BSL50)**, intended as the continuation of a historic trajectory up to 2050, including the energy transition but, without specific CE policies.
- **Ambitious circularity scenario (ACE50)**, which attains the higher circularity by 2050, while aiming for sustainability.

2.2.1 Status Quo 2020 scenario (STQ20)

This scenario reflects the sector in its current conditions, which is here represented by year 2020-2023, because of the data available on relevant flows of the supply chain. The status quo is used as a reference of comparison with the future 2050 scenarios (BSL50 and ACE50) to visualize the changes in production flows and associated impacts, also due to the anticipated energy transition towards a cleaner grid.

2.2.2 Baseline scenario (BSL50)

This scenario reflects the evolution of the cement and concrete sector during the time horizon investigated (2021-2050) based on historical trends. It implies that the EU CE policies contained in the Circular Economy Action Plans (CEAP 1 & 2) after 2015 are not included and therefore the

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[1] It needs to be underlined that for the cement & concrete sector, there are no policy targets for the future yet. Only the 2020 target from the 2008 Waste Framework Directive on a minimum of 70% recovery of construction and demolition waste by weight is applicable. This target has already been achieved, given the inclusion of backfilling as a recovery option. Therefore, in contrast to the aluminium, steel and plastics sectors, where respective future targets are set, there is no assessment of a policy compliance scenario.

trends between 2005 and 2019 are extrapolated (i.e. we assume CEAP 1& 2 policies have not had an impact on the available waste/materials statistics up to 2019). However, this scenario must account for all the remaining framework conditions such as the previous EU Waste Framework Directive (as of 2008 or earlier) and associated targets, as well as decarbonisation efforts occurring in the energy production sector. In line with the Better Regulation toolbox, this scenario thus represents a benchmark against which the benefits generated by the EU policies on CE can be estimated. The background conditions taken into account include:

- Demand for the (functional unit of the) material streams as external factors. While the demand of e.g. recycled materials can also be an endogenous variable, the demand of the function delivered by the product (irrespective of whether it is primary or secondary material) is estimated based on expert opinions and literature.
- Future energy mix, assumed to evolve towards a cleaner energy than the current one, in line with the energy mix projected by the Global Energy and Climate Outlook 2023 by JRC and DG CLIMA. This takes into consideration the deployment of decarbonisation technologies, such as carbon capture and storage or increased co-processing of waste for energy in cement production plants.
- Carbon price set by the EU Emission Trading System (ETS) as an external factor, which will come into force after the cement and concrete industry has benefited from free emission allowances to prevent carbon leakage. These free allowances are going to be phased out between 2026 and 2034 and instead complemented with the Carbon Border Adjustment Mechanism (CBAM). The latter requires reporting of carbon emissions from 2024 and then phases in a carbon price on imports from 2026 and 2034.

2.2.3 Ambitious circularity (ACE50)

This scenario reflects a normative scenario, in which an ambitious level of circularity is achieved in the cement and concrete sector based on the selection of a portfolio of R-strategies. Amid the different ways of increasing material circularity, the results support the identification of the most sustainable trajectory. This circularity scenario addresses both the issue of strategic autonomy (by ensuring the circulation of materials inside the EU), as well as the contribution of CE towards net-zero greenhouse gases (GHG) emissions by 2050. It needs to be underlined that the scenario is not modelled in a way to achieve net-zero emissions by 2050, but simply includes R-strategies that are reducing GHG emissions in parallel to decreasing mass flows. Moreover, the R-strategies are not employed at their technical maximum, but rather at an estimate defined by assumed future market conditions. The CE clusters outlined in Section **2.1** are functional to capture a wide spectrum of possible CE R-strategies which can bring about favourable sustainability impacts. Their implementation from a business and policy perspective requires introducing the notion of “circularity lever” (Bressanelli et al., 2021). This concept refers to specific interventions, and it has already been adopted by, for example, a recent study aiming to assess the economic and environmental impact of different circularity levers in a specific economic sector in the EU (SYSTEMIQ, 2022). In this study, we define the notion of a circularity lever as follows:

A circularity lever is a specific intervention based on one or more circular economy R-strategies, applied in the context of a particular material and sector, to increase resource efficiency, material durability and recirculation.

In line therewith, a selection of suitable circularity levers in the EU cement & concrete sector is identified from literature, and the corresponding economic and environmental impacts on the material system assessed. The levers are clustered according to the respective CE clusters previously defined (i.e. reduce, reuse and recover). Moreover, they are categorised by mode of implementation, namely as administrative, economic, and technical levers (Kirchherr et al., 2018). Technical levers include advancements in processing and recycling technology, and product design, which can facilitate disassembly and material recovery. Administrative levers involve implementing policies that limit market access and regulate means of production. Economic levers include financial incentives, such as tax breaks or subsidies for businesses adopting CE R-strategies. In the current analysis, the focus lies on the technical levers, the implementation of which can be supported by both economic and administrative levers.

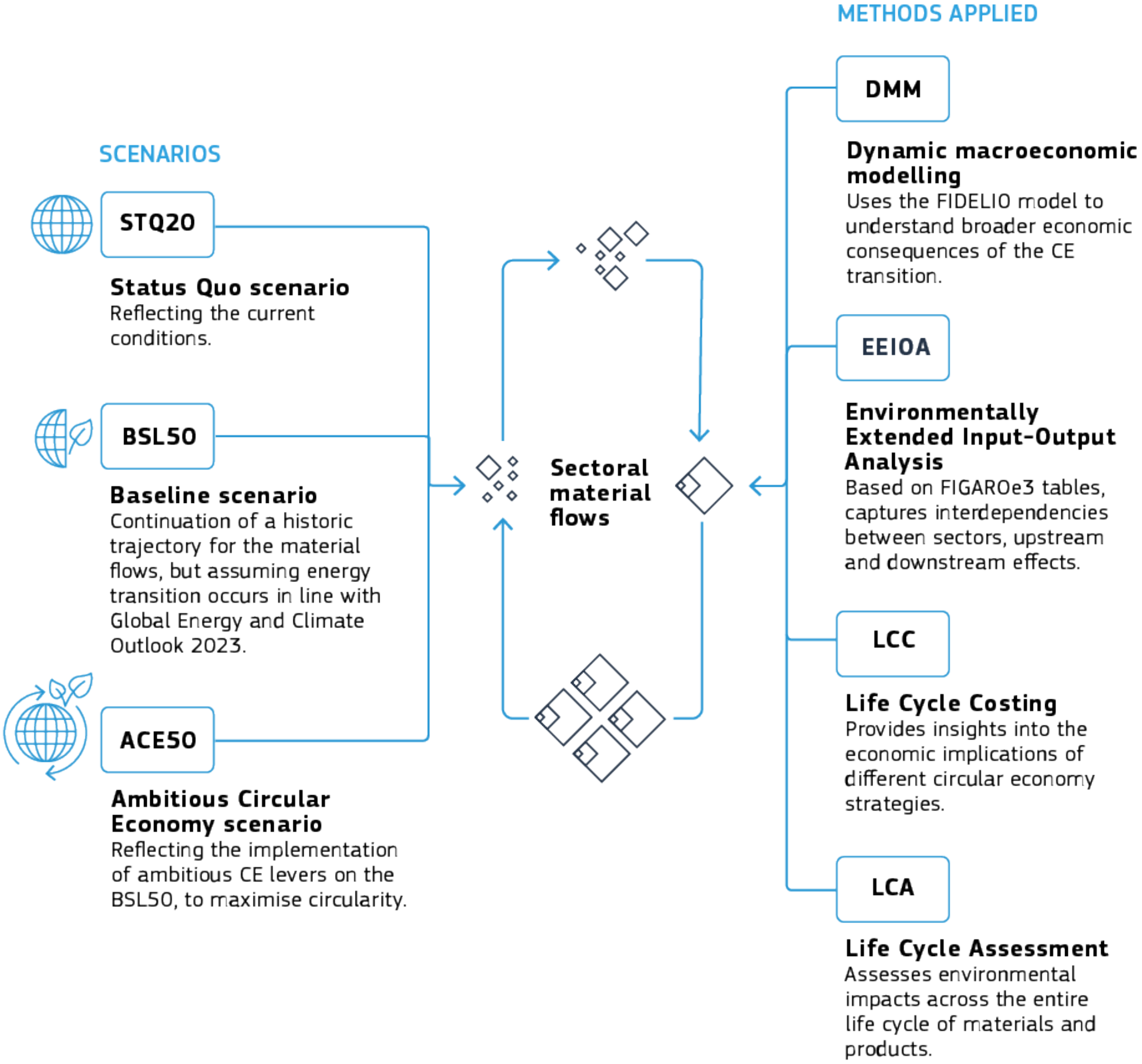
2.3 Research design

After defining the CE clusters and scenarios for this study, **Figure 4** shows an overview of the overall research design, lining out the assessed scenarios and a brief description of the life cycle-based and macroeconomic methods used. The methods applied in the study are characterised by either high granularity such as the Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), or high aggregation such as the Environmentally Extended Input-Output Analysis (EEIOA) and dynamic macroeconomic modelling. The combination of the bottom-up (i.e. high granularity) and top-down (i.e. high aggregation) methods is necessary to understand product systems in detail while concurrently capturing macroeconomic rebound and spillover effects. For example, LCA offers high granularity of material and product flows, but is limited in its ability to capture economy-wide impacts (incurring a truncation error), while EEIOA and dynamic macroeconomic modelling lack the detail for specific product assessments (incurring an aggregation error).

In terms of sequence, the three scenarios described in the previous subsection define the system boundaries, within which the material flows are embedded. These material flows are then assessed first, by means of LCA and LCC, the results of which then feed into the EEIOA and the dynamic macroeconomic modelling. While the individual methodologies are described in detail in **Section 3.1** (MFA), **Section 4.1** - **4.2** (LCA and LCC, respectively), **Section 5.1** (EEIOA) and **Section 6.1** (dynamic economic modelling), their main strengths and weaknesses, and their complementarities in view of our broader research questions are described here, while **Table 1** provides a comparative overview:

- Material flow analysis provides a detailed understanding of material flows. It includes the status quo and its projection up to 2050.
- LCA allows for the assessment of environmental impacts across the entire life cycle of materials and products. LCA is a linear accounting method and, as such, it does not account for macroeconomic effects, such as spillover effects across countries and economic sectors, effects due to changes in prices, investments, and trades. Sensitivity analyses are done on the side to test the most critical assumptions related to methodology and other aspects.

Figure 4. Research design of study



Source: JRC elaboration

- LCC provides insights into the changes in costs incurred by different circular economy strategies, given existing (gross) market prices. LCC is a linear accounting method and, as such, it does not account for macroeconomic effects such as spillover effects, changes in prices, investments, and trades.

- EEIOA, based on FIGAROe3 tables (Cazcarro et al., 2025), captures the interdependencies between sectors, allowing for analysis of upstream and downstream effects, including spillover effects across sectors. FIGARO tables provide a detailed representation of economic transactions between industries, which allows for the assessment of the flow of materials and emissions throughout the EU and Global economy. Relative to LCA and LCC, the added value of this analysis is a better understanding of the spillover effects and selected macroeconomic indicators, such as Gross Value Added (GVA) changes, Gross Domestic Product (GDP), employment, and resource dependency. However, EEIOA does not consider investments, price change effects, and change in trade patterns. Therefore, GDP and employment are better captured via dynamic macroeconomic modelling.

- Dynamic macroeconomic modelling provides a framework for understanding the broader economic consequences of the CE transition. The analysis is performed employing the FIDELIO model (Rocchi et al., 2025), a dynamic, multi-regional Input-Output model with new-Keynesian features, suitable for analysing medium-term transitions. It is designed to capture spillover and rebound effects, and quantify impacts on jobs, growth, energy savings, resource use, and trade balance. Additionally to the EEIOA, it accounts for investments, price change effects, and change in trade patterns offering a better angle on the full macroeconomic effects.

Table 1. Illustration of the scope, strength, limitations and complementarities of applied methods

Assessment Method	**Scope**	**Granularity**	**Strengths**	**Limitations**
Material Flow Analysis (MFA)	European cement & concrete supply chain.	The system boundary represents detailed flows of cement and concrete from production to waste management.	Detailed flows for the cement and concrete material system under assessment.	It is not always calculated as a dynamic material flow analysis
Life Cycle Assessment and Costing (LCA & LCC)	Limited to industry production and consumption in Europe, incl. waste management. The rest of the economy is truncated.	The system boundary represents detailed flows of cement and concrete from production to waste management within EU.	Detailed flows and supply chain representation for the cement and concrete material system under assessment.	Relative to EEIOA and DMM: Truncation error (it does not consider spillovers, investments, price change effects, and change in trade patterns).
Environmentally Extended Input-Output Analysis (EEIOA)	Global economy with disaggregated EU cement and concrete industry. The economy is not truncated.	The EU and Global economy are represented by 165 sectors (FIGARO IO tables); the EU cement and concrete sector is further disaggregated (sector C23E and C23F).	Interdependencies between EU and global economic sectors, spillover effects.	Relative to LCA: Aggregation error Relative to DMM: It does not consider investments, price change effects, and change in trade patterns.
Dynamic macroeconomic modelling	Global economy with aggregated industries. The economy is not truncated.	The EU and Global economy are represented by 64 sectors.	Investments, price change effects, and change in trade patterns.	Relative to LCA and EEIOA: Aggregation error.

DMM: dynamic macroeconomic modelling. EEIOA: Environmentally Extended Input-Output Analysis; LCA: Life Cycle Assessment; LCC: Life Cycle Costing

Source: JRC elaboration

3 Material Flow Analysis

To assess the performance of the EU economy in its transition to a more circular economy, and to provide guidance on the creation of effective CE policy instruments, a range of different methodologies are combined. They aim to identify the most promising CE lever(s) that, ultimately, can be transposed into policy options. The first methodology employed is material flow analysis (MFA), which then feeds into the bottom-up life cycle assessment (LCA) and life cycle costing (LCC) in a subsequent step. Before assessing the impact of material flows in the different scenarios, it is essential to understand how they are affected by the CE clusters – reduce, reuse and recover - in the ACE50 scenario. Therefore, the CE clusters are further subdivided into CE levers based on R-strategies, the effects of which are described in the following subchapter. Thereafter, the resulting MFAs provide the basis for the LCA and LCC as well as the subsequent top-down assessment approaches.

3.1 Methodology

Material flow analysis (MFA) allows for quantifying flows and stocks of a specific material (or substance) in a system, and serves as basis for the other methodologies employed in the assessment. The MFA of the cement and concrete system was developed based on data from CEMBUREAU (2023), Damgaard et al. (2022), Deetman et al. (2020), Shanks et al. (2019) and Woodward and Duffy (2011) . It consists of annual snapshots of the material flows in 2022 (including data points from previous years, in case those of 2022 were not available) and 2050. Moreover, the missing material flows are calibrated to the data points from industry as percentages, according to the composition of the material specified in the Ecoinvent 3.9.1 inventory or data from Environmental Product Declaration certificates from industry. It is essential to underline the large differences between MFAs in terms of predicting the stocks and flows. These depend on their type (stock or flow driven) and underlying assumptions with regards to population and real GDP growth, square meters (m^2) per person, as well as the building lifetime model applied (S. P. Deetman, 2021; Deng et al., 2023). Whereas the studies of S. Deetman et al. 2020 and Lotz et al. (2024) show considerable differences in both concrete inflows and outflows, as well as the ratio between the two, when compared to the data used here (Damgaard et al., 2022), the current and projected size of concrete stock are in a similar range of magnitude. Annex 1 provides an overview of the references per material flow.

The following paragraphs describe the modelling of three MFAs. In the Status Quo Scenario, the overall system in its current form is described in detail. It is followed by the Baseline Scenario 2050 description, containing key assumptions regarding future material flows and the subchapter on the Ambitious Circularity Scenario introduces the CE levers applied to the system.

3.1.1 Status quo

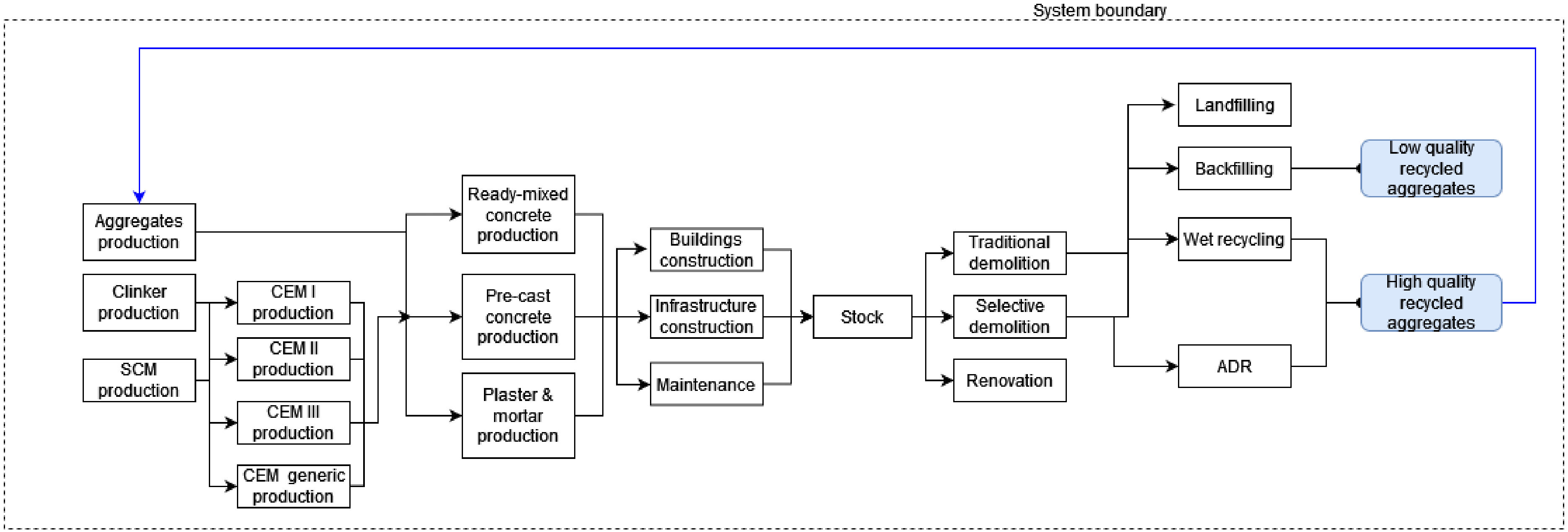
While the data points composing the material flows stem from different years (from 2015-2022), it is assumed that the relative composition of the materials does not change significantly between the years. As the cement demand is considered the main diver of the system, all material flows are calibrated to the amount of cement put on the EU market in 2022. The boundaries of the MFA encompass all stages of the cement and concrete life cycle; from the raw material for cement and aggregates to final disposal of construction and demolition waste (i.e. following a cradle-to-grave approach). An overview of the material system is presented in **Figure 5**. Imports and exports of cement are not included, given their marginal importance, with a net trade of 2 million metric tonnes

(Mt) relative to an overall production of 171 Mt (CEMBUREAU, 2022) and are expected to stay in the same range of magnitude in 2050 as they are currently. With regards to concrete, it is not a material that is traded with third countries, due to its weight. Cement is subdivided into CEM I (18%), CEM II (47%), CEM III (8%), and generic cement (27%). These different types of cement then are mixed with aggregates into ready-mixed concrete (56%), pre-cast concrete (18%) and plasters and mortars (26%) (CEMBUREAU, 2022). The industry sector is construction, using concrete in buildings (50%), infrastructure (30%) and maintenance services (20%). A further subdivision into residential and non-residential buildings was not considered, given the similar end of life (Damgaard et al., 2022).

The material flows entering the end of life are determined as a percentage of the inflows, in line with the background data by Damgaard et al. (2022). Construction and demolition waste either follows traditional demolition, selective demolition or renovation. As anticipated, the latter is minimal in the case of concrete and modelled by Damgaard et al. (2022) as a flow that is present both on the construction and demolition side. While renovation is to be assumed part of the maintenance fraction on the inflow side, it is nevertheless singled out from the demolition on the outflow side. To date, there is no clear data on the percentage of selective demolition in Europe, but only of selected countries (Luciano et al., 2022; Pristerà et al., 2024). Therefore, it is assumed that a majority of the total landfilled (13%) and backfilled (11%) material goes through traditional demolition, while one third of the recycled material (0.67 x 77%) undergoes selective demolition instead (Caro et al., 2024). It needs to be underlined that the 77% is most likely an overestimation, since several European countries do not differentiate between recycling and backfilling (Moschen-Schimek et al., 2023).

The material streams from selective demolition are either backfilled (estimated at 10%), landfilled (at 8%) (Iodice et al., 2021) or undergo one of two recycling processes. On the one hand, 95% are assumed to undergo wet recycling (Etxeberria et al., 2022; Zhang et al., 2019), yielding high quality washed recycled concrete in two different orders of granularity, which replace gravel and sand respectively. On the other hand, a more recent technology employed for 5% of the material streams coming from selective demolition is the Advanced Dry Recovery (ADR) recycling. This system can be complemented with a Heating Air classification System (HAS), producing high quality recycled concrete in three different material fractions (Gebremariam et al., 2020). For the status quo and the BSL50 scenarios, only ADR, producing coarse and fine recycled concrete aggregates, is considered. For reasons of simplicity, the recycled aggregates are visualised to flow back into the construction of concrete, even though it is acknowledged that the aggregates might also be used for other purposes such as for road base or unbound uses. In general, about 8-10% of all aggregates used are recycled aggregates, though the share of recycled aggregates used for concrete is not established (Pacheco et al., 2023).

Figure 5. Material system in STQ20 scenario in the cement and concrete sector

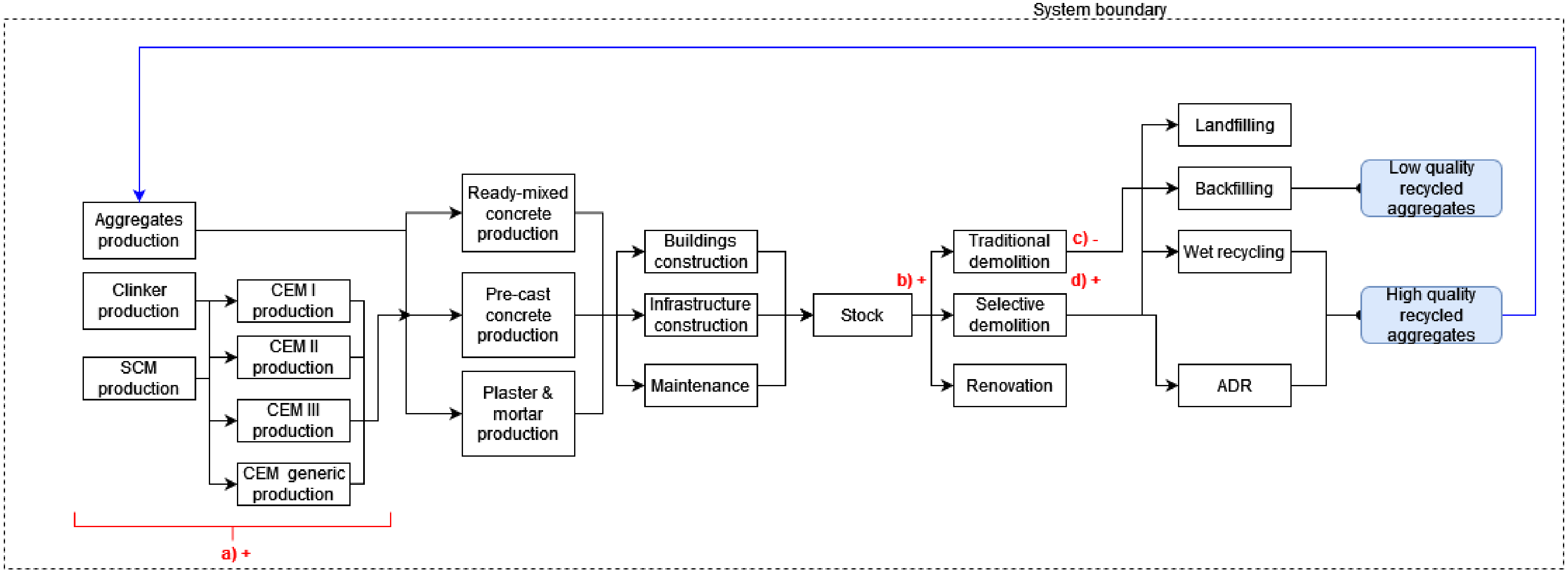


Source: JRC elaboration

3.1.2 Baseline 2050

For 2050, the Status Quo system is scaled in line with demand forecasts for cement of Material Economics (2019) and Nilsson et al. (2020) to represent the Baseline 2050 system. While this is not a dynamic MFA, the expected trends point to an increase of cement production until 2030 and a subsequent plateau, or even slight decrease, due to slowing population and GDP growth. Moreover, the demolition rate (representing the construction outflow per total inflow) is adapted to the absolute magnitude predicted by Damgaard et al. (2022). Whereas the construction increase of buildings in 2050 is assumed to be higher by Damgaard et al. (2022) than the industry projections, the absolute mass of waste concrete is considered suitable for use nevertheless. This is, on the one hand, due to the time lag of demolition, and, on the other, because of the similar construction mass flows predicted for 2020. Combining these two data points of future cement demand and C&DW outflows, the demolition rate shows an increase from 11% (compared to the construction inflows) in 2020, to 27% in 2050. The reason for this increase is the waxing construction stock, with more buildings reaching their end of life. Finally, some recycling flows are partially rerouted at the end of life. Given the increased informative instruments on C&DW (such as end-of-waste criteria and update of pre-demolition audit guidelines) and pressure from industry associations to increase selective demolition, it is expected that an increased share of materials (50% of outflows) is going to undergo selective demolition. As the overall share of landfilling and backfilling is set to be the same as in status quo, the share of material from the traditional demolition to landfill is slightly higher, at 18%, as opposed to the 15% in status quo. The backfilling is projected to stay at 10% for both traditional and selective demolition. With regards to recycling, the model assumes that the wet recycling process and ADR will each account for half of the remaining material flows from selective demolition. **Figure 6** displays the so-called first order effects, namely the immediate changes of material affected by the described changes (i.e. increased demand, demolition rate and share of selective demolition).

Figure 6. Material system in BSL50 scenario in the cement and concrete sector with first order effect of changes



Notes: a) demand increase of cement, b) demolition rate increase, c) decrease of traditional demolition, d) increase of selective demolition

Source: JRC elaboration

3.1.3 Ambitious circularity 2050

In addition to the changes outlined in the Baseline 2050 Scenario, the material flows in the Ambitious Circularity Scenario are affected by the aforementioned CE levers. The list of levers identified for the EU cement and concrete sector is presented briefly in **Table 2.** Overview and categorization of circularity levers in the EU cement & concrete applied in *Ambitious circularity scenario***Table 2**. It reports the reduction of material flows relative to the Status Quo value and the first order effect on the affected flows. Given that the production hotspot of cement and concrete is the clinker production, the material flow that is intended to be reduced, reused and recovered is clinker and its usages (including cement, and concrete). For an in-depth description of each lever, their combination, and the modelling parameters for the environmental and economic assessments, consult **Annex 2**. As to get a better understanding of the first order effects, the changes are highlighted in **Figure 7,** depicting the material system for the ACE Scenario. It can be observed that the levers take effects throughout the whole cement and concrete life cycle, though there are certain trends. Levers related to reduction are mostly situated at the beginning of the life cycle. Levers connected to the reuse cluster are located towards the middle of the life cycle and in the case of L7 (lifetime extension) affect both material inflows and outflows of the stock. L8 (reuse of concrete) differs in that it first requires the material to undergo selective demolition, before it can be reused at a different site. Another observation is that some levers only have one first order effect (e.g. L1, reduction of raw material, L5 reduction of cement, L6 reduction of concrete), given that the same material function is fulfilled with less primary material. L4 (concrete substitution) is different in this regard, because the material is substituted by timber, thus indicating an addition material flow from another system, which has a different end of life and is this not depicted in **Figure 7**. Other levers indicate a trade-off between material flows. For levers related to reduction, e.g. L2 (clinker substitution), clinker production is reduced while the use of supplementary cementitious materials is increased, or L3, where the use of alternative binders decreases the use of CEM I, II and III. Similarly, at the end of life, L11 (recycling to concrete) deviates material flows from the landfilling and backfilling stream to wet recycling. Likewise, both L9 and L10 (recycling to raw material and cement, respectively), reroute material flows from the production of recycled aggregates through ADR only, to recycled cement fines produced by the HAS. Finally, backfilling has consciously been excluded as a lever, given it is considered downcycling and is not included in the calculation of the secondary material stream making up the circular material use rate (Eurostat, 2018).

Levers thus imply substitution of virgin material with input from other material systems, which can be by-products (as in the case of supplementary cementitious materials such as fly ash or blast furnace slag) or virgin products (e.g. cross-laminated timber). As to materials recirculating within the material system, these comprise reused concrete, recycled aggregates and cement fines, replacing virgin concrete, gravel and sand, as well as cement and calcareous marl respectively. In addition to the two fractions replacing gravel and sand, the finest material fraction can partially replace raw material for clinker and cement (Moreno-Juez et al., 2020). However, it needs to be acknowledged that the capacity of the HAS technology is still limited and is expected to stay constant, as to account for the diffusion of the technology as such, which to date has mostly been used in the Netherlands only (Zhang, Hu, Dong, Gebremariam, Miranda-Xicotencatl, et al., 2019).

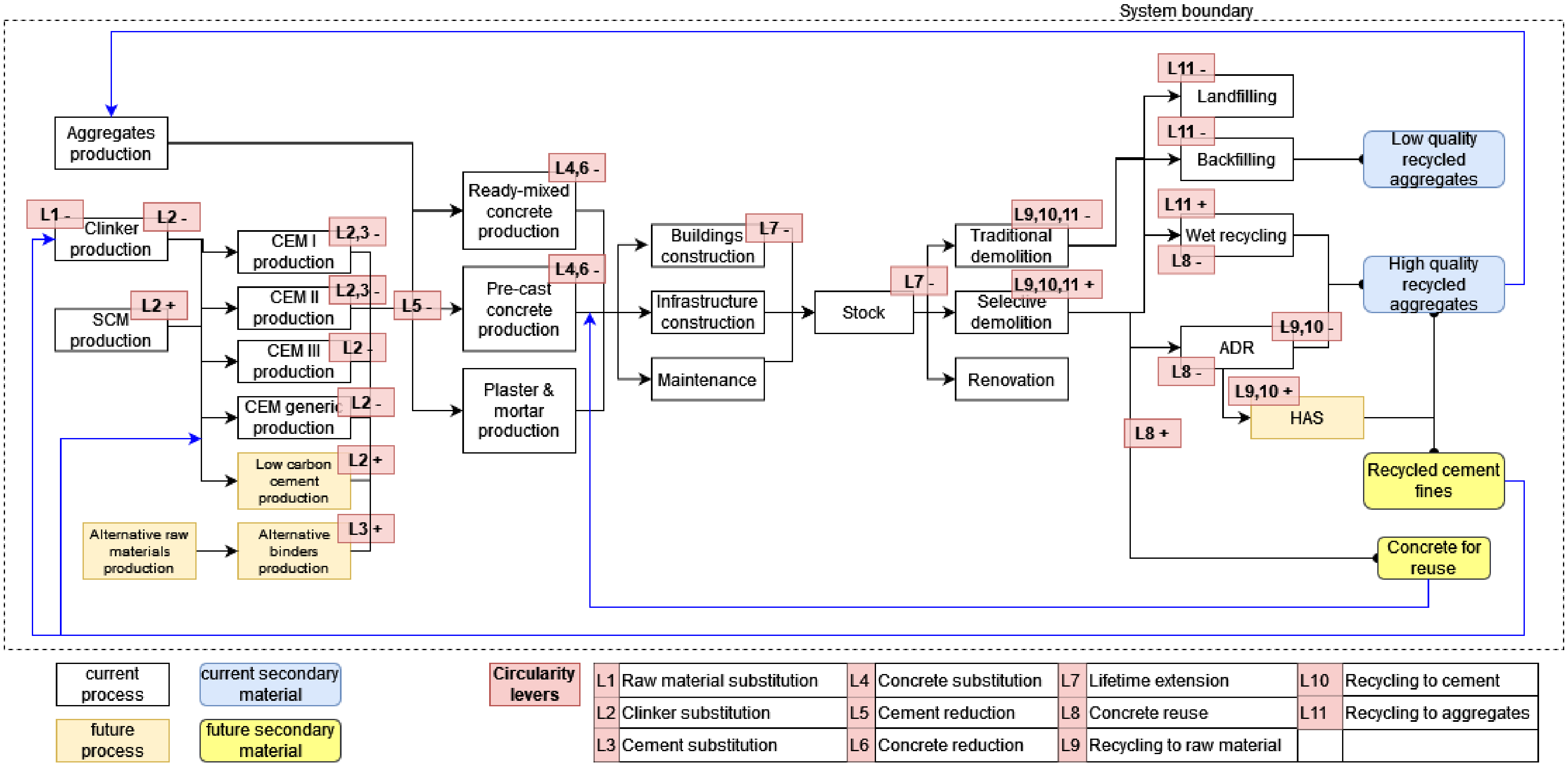
Table 2. Overview and categorization of circularity levers in the EU cement & concrete applied in *Ambitious circularity scenario*

CE cluster	CE lever		Description	Quantification by 2050	First order effects	End-use	Source
Reduce resource input (Reduce)	1	Clinker raw material substitution	Substitute raw materials of clinker with mineral ashes obtained by co-processing waste for energy production in the cement kiln	From 0% to 5% of raw material	Reduced calcareous marl input	Clinker	Viczek et al., 2020
	2	Clinker substitution	Substitute clinker in cement through other supplementary cementitious materials (SCMs) such as calcined clay, fly ash or pozzolans	From 23% up to 43% of SCMs	Reduced clinker input and increase of SCMs, used in low carbon cement	Cement	Material Economics, 2019; Favier et al., 2018; Nilsson et al., 2020
	3	Cement substitution	Substitute cement with alternative cement such as calcium sulfo aluminate cement and carbonatable calcium silicate cement, which have lower environmental impacts	7-10%	Reduced cement input and input of alternative binders	Cement	Chen et al., 2012; Gartner & Sui, 2018; Miller & Myers, 2020; Favier et al., 2018; IEA & WBCSD, 2018; Nilsson & Verschaeve, 2022
	4	Concrete substitution	Substitute concrete with wood in the form of cross laminated timber and solid glued timber in structural elements for buildings	Replace up to 5-10% of the current concrete demand for buildings	Reduced pre-cast and ready-mixed concrete input and increased timber input	Concrete	Material Economics 2019; Agora Industrie & Systemiq, 2023
	5	Cement reduction	Reduce amount of cement in concrete for buildings through following concrete standards more closely	Up to 5% reduction of current cement demand	Reduced cement input	Concrete	Favier et al. (2018)
	6	Concrete reduction	Reduce amount of concrete in buildings while maintaining structural properties through	Up to 30-40% reduction of concrete	Reduced concrete input for buildings	Buildings	Favier et al. (2018); Material Economics, 2019

			following building standards more closely	demands in buildings			
Slow resource throughput (Reuse)	7	Lifetime increase	Increase lifetime of buildings through renovation and reuse of concrete structure, reducing the demand for construction and decreasing demolition	Increase from 70 to 90 years	Reduced construction of buildings and reduced demolition	Buildings	Favier et al. (2018); Agora Industry & Material Economics, 2022
	8	Concrete reuse	Reuse pre-cast elements of buildings at other sites after selective demolition and quality assessment	Up to 15-20% of precast concrete at EoL is reused	Increased reuse of pre-cast concrete to replace primary concrete	Buildings	Material Economics, 2018, Pristerá et al., 2024
Enhance resource recirculation (Recover)	9	Recycle concrete to clinker raw material	Recycle concrete and use fines as raw material for clinker, mainly replacing calcareous marl	Up to 20% replacement is claimed though technically only 5% are recommended, and market availability is limited	Increased recycling through ADR and HAS to replace calcareous marl	Clinker	Krour et al., 2020; Diliberto et al.; 2017; Favier et al., 2020
	10	Recycle concrete to cement	Recycle concrete and use cement fines as supplementary cementitious materials for cement	Up to 10% replacement are possible, though only 5% are recommended, and market availability is limited	Increased recycling through ADR and HAS to replace cement	Cement	Moreno-Juez et al., 2020; Gebremariam et al., 2020; Agora Industry & Material Economics, 2022
	11	Recycle concrete to aggregates	Recycle concrete into recycled aggregates for new concrete (closing the loop), differentiating between coarse and fine aggregates	Up to 95% of concrete is recycled to recycled aggregates	Increased wet recycling to replace primary aggregates and decreased landfilling and backfilling	Concrete	Le & Bui, 2020; Lotfi et al., 2015, Pacheco et al., 2023

Source: JRC elaboration

Figure 7. Material system in Ambitious Circularity 2050 Scenario in the cement and concrete sector with first order effects of changes induced by levers



L1	Raw material substitution	L4	Concrete substitution	L7	Lifetime extension	L10	Recycling to cement
L2	Clinker substitution	L5	Cement reduction	L8	Concrete reuse	L11	Recycling to aggregates
L3	Cement substitution	L6	Concrete reduction	L9	Recycling to raw material		

Note: Levers are labelled by numbers, with either positive (+) or negative (-) effects on material flows

Source: JRC elaboration

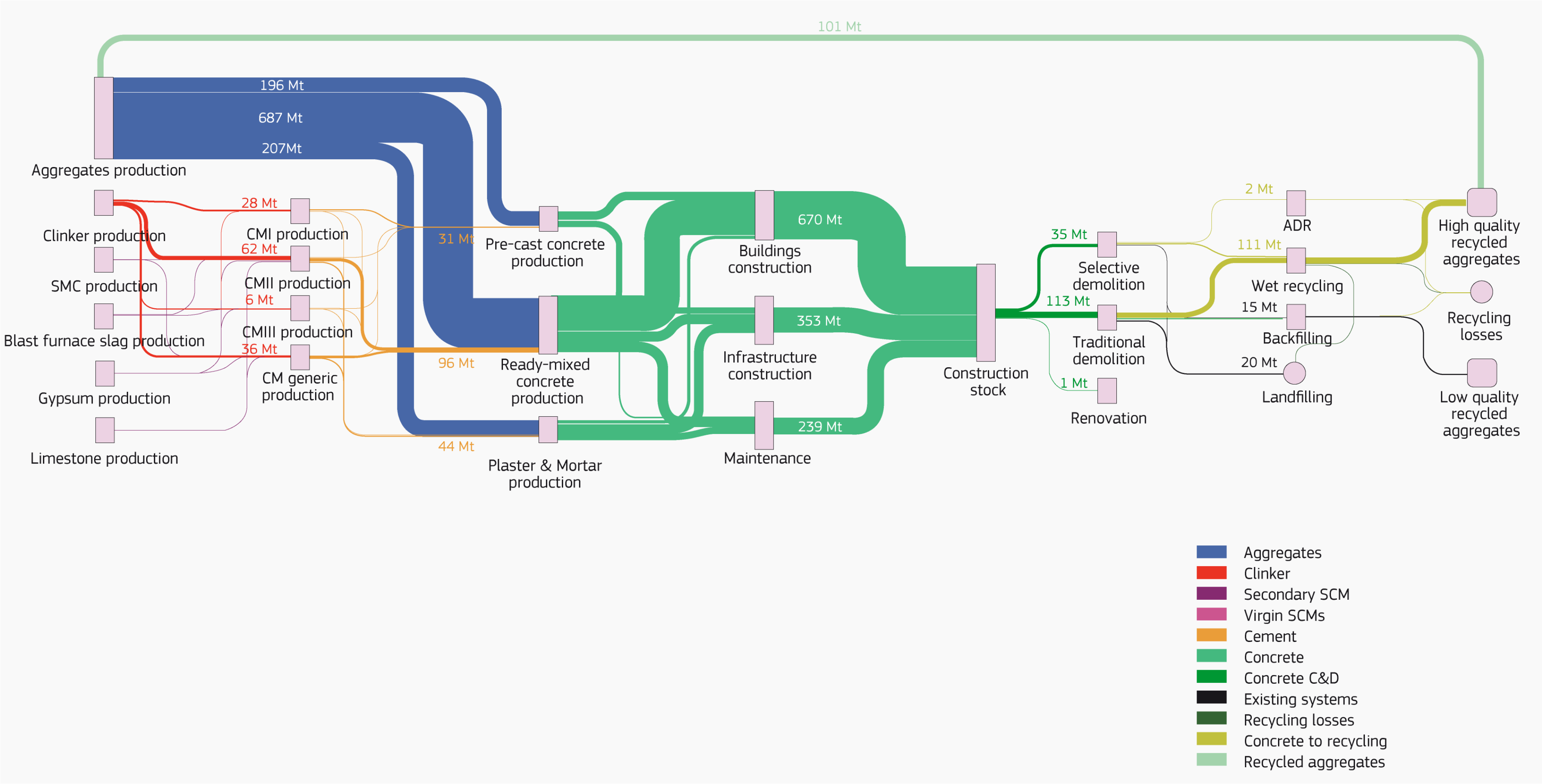
3.2 Results

An overview of the material flows in the cement and concrete sector are presented in **Figure 8**. The total amount of cement produced and consumed is estimated at 171 Mt, requiring about 132 Mt of clinker, with a clinker to cement ratio of 77%. The corresponding aggregates needed for the different types of concrete are 687 Mt for ready-mixed concrete, 196 Mt for pre-cast concrete, and 207 Mt for plasters and mortar. Thereof, between 8-10% of aggregates are expected to come from recycled materials. The total amount of concrete flowing into the building stock is thus 1262 Mt per year. In relation thereto, demolition is about 10x lower, at 148 Mt, of which 113 Mt are traditional, and 35 Mt are selective. Overall landfilling is 20 Mt and backfilling is 15 Mt, both mainly stemming from traditional demolition. Recycling makes up about 113 Mt of the end-of-life material streams and yields 101 Mt of recycled concrete aggregates, which can either be used for concrete production (limited fraction) or other bound (mainly road-base) or unbound applications. The difference between recycling input and output are attributed to losses in quality as well as the creation of sludge (3 Mt), to be treated at landfills.

This material system is then scaled by the cement demand increase for 2050 to 182 Mt, as well as an increase in the demolition rate to 27%. **Figure 9** shows the resulting Sankey Diagram. It can be observed that the material inflows remain the same, besides being scaled by 6.43% until they reach the stock. It is only at the end of life, that the higher demolition rate increases the material outflows by 153.58%. While the traditional demolition stream increases by 66.21%, the flows going through selective demolition increase by 439.66%. Despite the reduction in traditional demolition, both landfilling and backfilling are increasing by about 150%, due to the higher share of demolition. The recycling stream increases by 139.35% compared to the STQ scenario. Therefore, wet processing, previously accounting for 95% of recycled streams increases by 89.86%, while the stream undergoing ADR is over 400x higher than in the STQ scenario. This yields recycled concrete aggregates of 260 Mt, more than doubling that of STQ scenario. It is still expected that only a small fraction of these recycled concrete aggregates will substitute gravel for making concrete, and instead, the majority is expected to be used as road-base or filling for foundations.

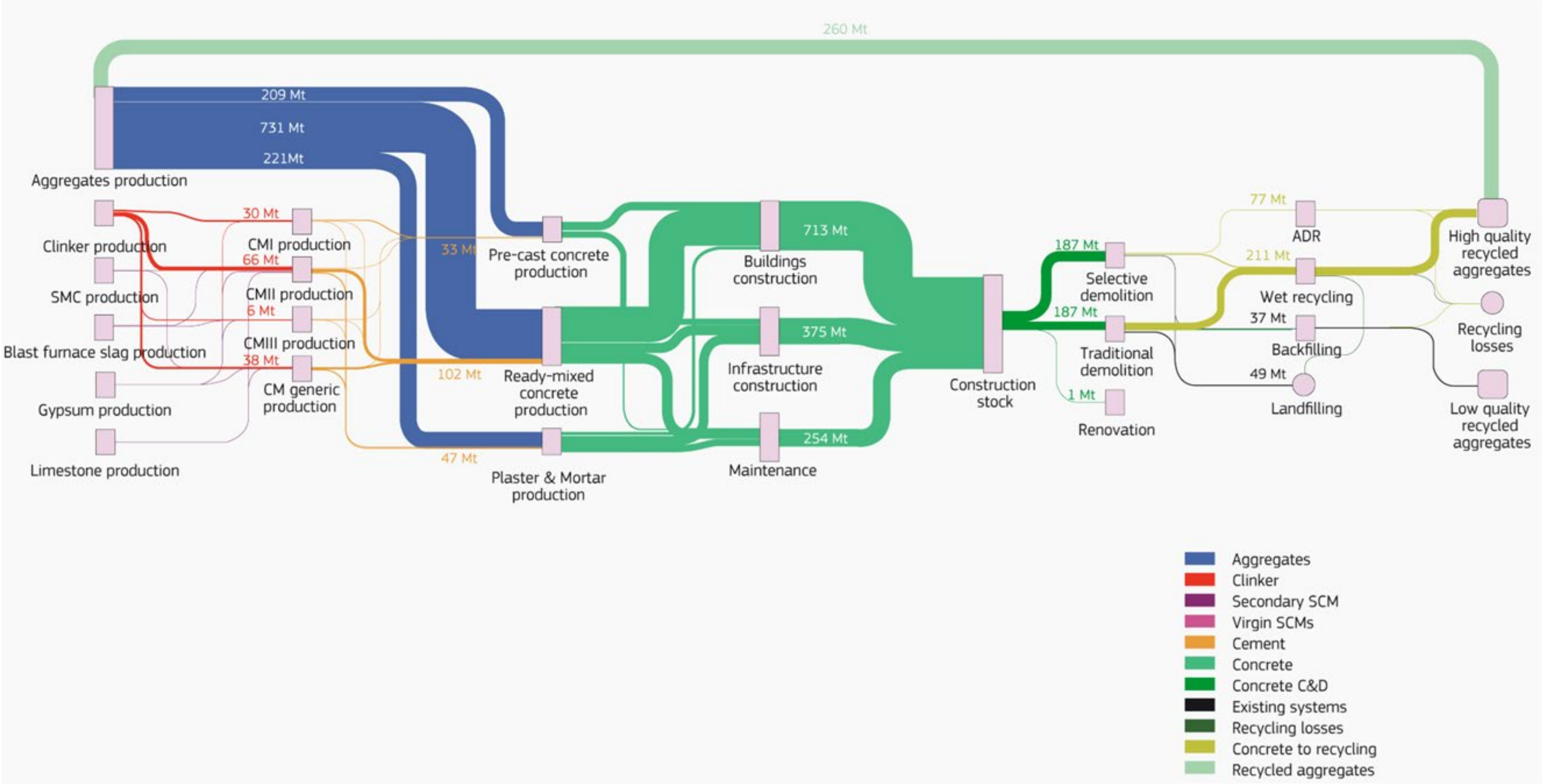
When comparing the material flows if the BSL scenario to those of the ACE scenario, presented in **Figure 10**, clinker is reduced by about 50% to 70 Mt, while this reduction is 5% smaller with regards to the STQ scenario, given the lower amount of cement produced. There is also a 78.29% increase in the use of SCMs in CEM II and generic cement, not yet including the additional virgin materials such as limestone and calcined clay for the low carbon cement. Cement production overall is reduced by 28% to 131 Mt, while the strongest reductions are CEM I and CEM III in relative terms, and CEM II in absolute terms. The use of aggregates for concrete is reduced by 28.26%, while the reductions for the different types of concrete are between 27.61% (Pre-cast concrete) and 29.73% (Plaster & mortar). These reductions are translated to the three construction types (buildings, infrastructure and maintenance) and result in a 28.22% decrease in inflow to the building stock (964 Mt), similar to the decrease in cement. As the levers related to recovery assume a higher rate of selective demolition, traditional demolition is decreasing by 91.18% with respect to the BSL scenario, while selective demolition is increasing by 67.61%. Landfilling is reduced to 0 and backfilling by 95.59%, due to the increased recycling through lever L11, rerouting the remaining material flows to the wet recycling process, ADR and the reuse of concrete (L10). Wet recycling decreases by 23.31%, whereas ADR increases by 103.39%. In comparison to the BSL scenario, there is also material flows undergoing the HAS (62 Mt), using the fine fraction coming out of the ADR as well as the reuse of concrete (10 Mt), directly subtracted from the material flow previously destined for wet recycling. The mass of recycled concrete aggregates is 279 Mt, while recycled cement fines account for 9 Mt. Recycled aggregates are expected to remain open loop, whereas recycled cement fines are expected to go back into the cement and concrete life cycle.

Figure 8. Sankey diagram in Status Quo Scenario (STQ20) of cement and concrete material flows



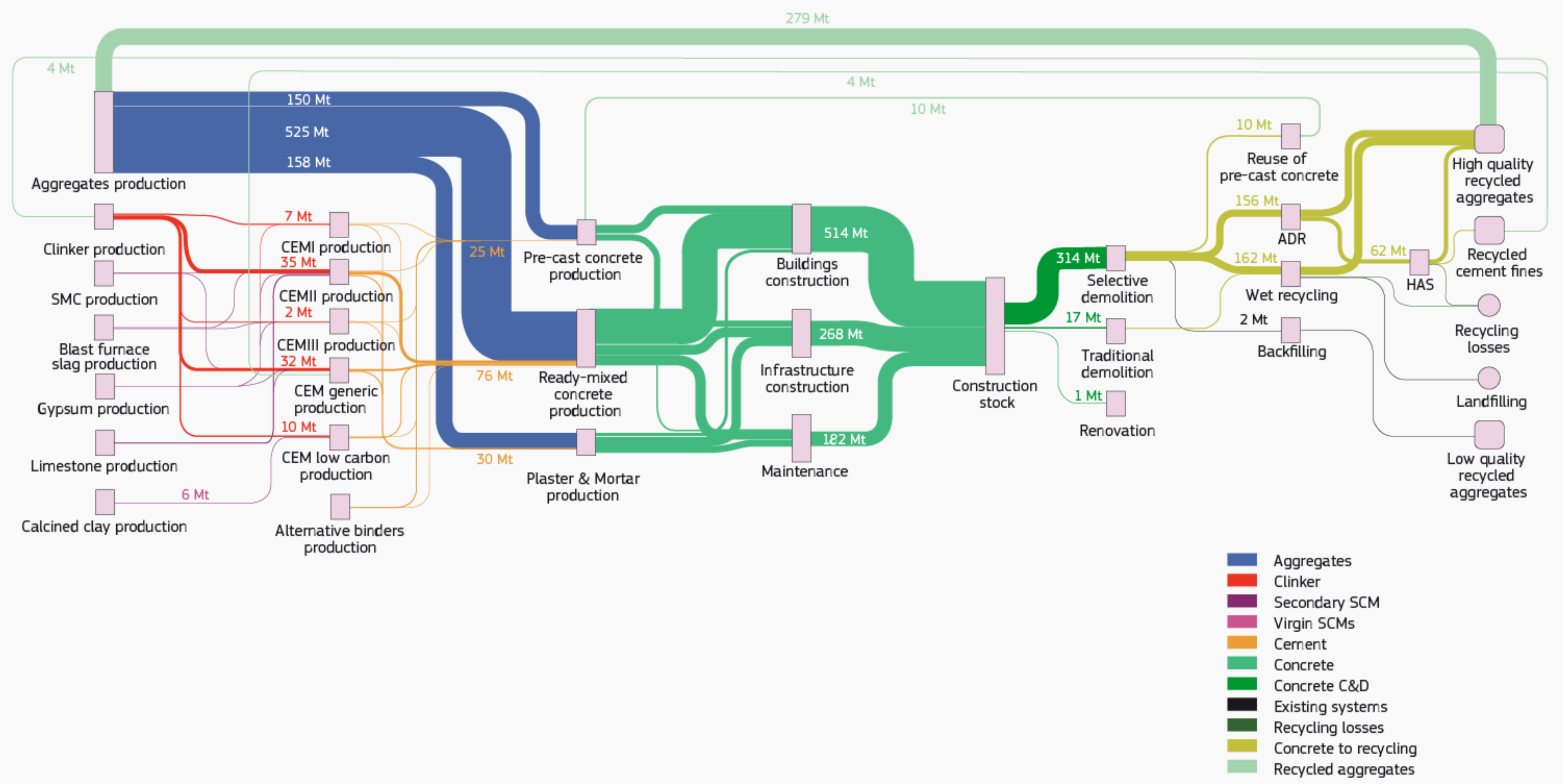
Source: JRC elaboration

Figure 9. Sankey diagram in Baseline 2050 Scenario (BSL50) of cement and concrete material flows



Source: JRC elaboration

Figure 10. Sankey diagram in Ambitious Circularity Scenario (ACE50) of material flows in the cement and concrete sector



Source: JRC elaboration

4 Life cycle assessment and costing

This section details the life cycle assessment (LCA) and life cycle costing (LCC) methodologies used to quantify the environmental and economic impacts with a bottom-up approach. **Section 4.1** details the general features of the LCA methodology, while **Section 4.2** describes the LCC methodology. In addition to the environmental and economic impacts, the secondary material used to substitute primary material is also quantified as an impact category. It is determined to calculate the circular material use rate (CMUR), which is obtained by dividing the use of secondary material used for satisfying demand by the overall material use (Eurostat, 2018). In contrast to the MFA, the use of secondary materials from different material cycles (e.g. by-products of other industries) are neither considered in the secondary material use nor the CMUR, due to its definition. Given the specificity of the construction sector, it is further essential to underline that the results of the CMUR do not necessarily represent increased demand for recycled materials or circularity, but could also increase due to higher demolition rates, as identified in the MFA. Therefore, the CMUR is expected to increase due to structural features of the sector (I.e. a high material stock and decreasing inflow), rather than the active deployment of more recycling technologies or overall demand decrease.

4.1 Methodology LCA

The LCA has been carried out in accordance with the guidelines of the ISO 14040/14044 standards (ISO, 2006a, 2006b). The scope of the LCA is the European cement and concrete supply chain, with the overarching goal of quantifying the environmental impacts associated to it in 2021 and 2050 under two different scenarios, defined in section 2.2. Given the analysis is assessing a future material system, it can be considered a prospective LCA (Arvidsson et al., 2023). Even though prospective LCAs have traditionally been connected to emerging technologies, Arvidsson et al. (2023) argue to unify future-oriented LCA under the definition of prospective LCA as an *"LCA that models the product system at a future point in time relative to the time at which the study is conducted"* (p. 5). In contrast to traditional LCAs, critical aspects to be defined are the exact point in time in the future, the technological maturity and upscaling of systems modelled, scenario development (described in sections 2.2, 4.3), the involvement of stakeholders (see section 4.3.5) and the use of background data, further specified in the following sections. A limitation is that the life cycle impact assessment used has not been adapted to future impacts in terms of characterisation factors, as research on this is only available for a subset of impact categories with considerable uncertainties (Arvidsson et al., 2023). By taking into account the aforementioned issues, the prospective LCA can be considered as inspired by the more structured methodology proposed by Langkau et al. (2023), yet does not follow each step systematically.

4.1.1 Goal and scope

The analysis covers all cement and concrete streams produced and consumed in the EU, therefore defining the functional unit as the mass of cement-containing materials flowing in the EU per year of reference. This mass is affected by the cumulative implementation of the CE levers and, due to the absence of import and export can also be referred to as the demand for cement-containing materials. The system boundaries of the assessment are equal to those presented in **Figure 5-7** and include processes from raw material inputs for clinker, supplementary cementitious materials and aggregates to final disposal of construction and demolition waste, including both landfilling and recycling options (i.e. following a cradle-to-grave approach). Only the process of constructing the structure itself (i.e. building, infrastructure and maintenance), as well as its use phase are excluded. The reason for this is that the impacts are expected to be similar in the Status Quo, Baseline 2050 and the Ambitious Circularity scenario in terms of material use while the effects on labour are not known to a sufficient degree as to model them here. However, this might lead to underestimating differences of the reuse cluster levers, if for instance the energy efficiency of old buildings is not increased. These differences could be assessed in a separate study, with a more user-centred focus. To address multi-functionalities that may arise in the system, either at production or at end-of-life, system expansion is performed following common practices (ISO, 2006a, 2006b; Laurent, Bakas, et al., 2014; Laurent, Clavreul, et al., 2014). Therefore, for example, recyclates that arise from managing the waste are credited to the waste management system by assuming the displacement of the virgin counterparts, corrected by a substitutability factor. Background life cycle impact assessment data are obtained from the ecoinvent v3.9.1 database, following the ‘allocation at the point of substitution’ modelling approach (Wernet et al., 2016). To model the electricity and heat average mixes, the official Global Energy and Climate Outlook (GECO) projections of the European Commission Joint Research Centre are used (further described in **Section 4.1.4**; Keramidas et al., 2023). The use of these projections has a similar function as for example the employment of the REMIND or IMAGE database of future energy scenarios (Sacchi et al., 2022; Stehfest et al., 2014), as is good practice in prospective LCA, also in connection with cement production (Cavalett et al., 2024; Georgiades et al., 2023; A. Müller et al., 2024). It needs to be underlined, however, that in contrast to using these databases, which are altering the energy processes in ecoinvent databases, the GECO 2023 data is only applied to foreground processes and not for e.g. the extraction of raw materials. These rely on the unaltered ecoinvent v.3.9.1 processes, which can lead to minor distortions of the result.

The environmental impacts are quantified following the Environmental Footprint Life Cycle Impact Assessment method (EF, v3.1) (Andreasi Bassi et al., 2023). All its 16 environmental impact categories are considered, namely: Climate Change; Ozone Depletion; Human Toxicity, cancer; Human Toxicity, non-cancer; Particulate Matter; Ionising Radiation; Photochemical Ozone Formation; Acidification; Eutrophication, terrestrial; Eutrophication, freshwater; Eutrophication, marine; Ecotoxicity, freshwater; Land Use; Water Use; Resource Use, minerals and metals; and, Resource Use, energy carrier. The LCA software EASETECH v.3.6.0 was used, as it allows for detailed modelling of waste processes (Astrup et al., 2012; Clavreul et al., 2014).

4.1.2 Modelling assumptions and life cycle inventory of material flows

The life cycle inventory of the material flows follows the three MFAs determined in subchapter 3.1. More detailed descriptions of the modelling assumptions and life cycle inventory are reported in Annex 3. The processes considered in the LCA are mainly based on the inventories reported in the EPDs published by CEMBUREAU, Ecoinvent 3.9.1 processes and complemented by scholarly references. The processes include both material input as well as machinery. The latter are either taken from Ecoinvent (for production processes) or literature (Butera et al., 2015; Zhang, Hu, Dong, Gebremariam, Miranda-Xicotencatl, et al., 2019) (for recycling technologies). Regarding the implementation of the levers, it is important to note that they have been implemented in three distinct ways: i) separately by lever, ii) grouped by CE cluster as well as iii) aggregated circularity, to isolate the effects of the individual levers and identify how they are interconnected. The rationale by which they are combined is available in in **Annex 2**.

4.1.3 Foreground modelling of rotary kiln heat and CCS implementation at plant

As the production of clinker is the most energy-intensive and thus environmentally sensitive process of cement and concrete production, this part of the lifecycle is potentially most susceptible to modelling changes (Sousa & Bogas, 2021). The thermal efficiency of the kiln was modelled according to Georgiades et al. (2023), assuming a dry kiln with a preheater and pre-calciner for 2050. The emissions of the energy consumption inside the rotary kiln were modelled in line with the heat mix developed by García-Gutierrez et al. (2023) with the corresponding emissions to air, water and soil. This also yields the weight of the bottom ash resulting from the combustion, which can partially be taken up by the clinker itself as a raw material (Alarcón et al., 2022). The composition of the heat mix is in line with the projections of CEMBUREAU (2023), aiming to increase the share of waste to fuel up to 95%, with a 50% biomass content by 2050. Both the availability of the biomass and waste used for co-processing are expected to be a constrained resource by 2050 (Material Economics, 2019). Therefore, an assessment of the counterfactual treatment options for the waste (e.g. recycling or landfilling) would be prudent to capture the full scale of (avoided) emissions. However, given the focus of this study on circularity, rather than decarbonisation and the considerable uncertainty of the modelling assumptions, the different end of life options were not included.

Moreover, industry forecasts that the use of CCS is unavoidable for the cement sector in the future, due to the process emission released during the calcination of limestone (ETC, 2022). Whereas the exact implementation rate at cement factories varies across prognoses and scenarios, and in some instances goes up to 80% in techno-optimist models (CEMBUREAU, 2020; Material Economics, 2019), the current study applies a more conservative coverage rate of 25% by 2050, matching the projection of Cavalett et al. (2024). In comparison to the 15% CCS coverage of the GECO report, further elaborated on below, 25% refers to CCS related to clinker production only, and not to the whole non-metallic minerals sector. The technology at plant level is either the post-combustion technology monoethanolamine (MEA) CCS, with a higher TRL or the increasingly popular Oxyfuel CCS, modelled according to Georgiades et al. (2023), each accounting for half of the 25% coverage rate. The emission reductions are directly applied in the lifecycle inventories of both the production process (in the case of calcination emissions) and the energy-related emissions, also taking into account the capturing of SO_x and NO_x besides CO_2 (A. Müller et al., 2024). Energy use and related cost increases per tonne of clinker are determined by literature documenting existing CCS projects in cement plants and scholarly literature specific to the cement sector (Cavalett et al., 2024; Gardarsdottir et al., 2019; Gerbelová et al., 2017; Hills et al., 2017; Quantis, 2021; Voldsund et al., 2019) and presented in **Annex 3.**

4.1.4 Background energy modelling

The projections presented in the GECO 2023 update (Keramidas et al., 2023) are used to calculate the composition of the average energy mix, distinguishing amongst electricity, industrial heat (specific to the sector analysed), district heating, and space heating, of the EU from 2020 to 2050. Out of the three scenarios considered in the GECO 2023 (Keramidas et al., 2023), the Nationally Determined Contribution (NDC) Long-Term Strategies (LTS) is assumed as default energy mix. In this scenario, the targets of the NDC towards CO_2 reduction are considered in the medium and the longer term. Moreover, the scenario presupposes that the objectives in the NDCs are met in the target year (mostly 2030). Beyond 2030, whenever they exist, the LTS targets of the different countries or regions, as in the case of the EU, are pursued, which is the net-zero target for 2050 (Keramidas et al., 2023). In the GECO 2023 projection, transport is also decarbonised. However, for the sake of simplicity, the decarbonisation of the transport sector is not taken into account.

Within the NDC-LTS scenario, the energy grid is decarbonised due to high shares of renewables in the mix, but also as a result of the implementation of CCS. As mentioned in **Section 4.1.2**, ecoinvent datasets have been used for modelling the background processes, including the energy mixes. The life cycle inventories related to energy production from biomass, combined heat and power fuelled by natural gas, coal, lignite, natural gas, and oil, have been modified to account for the energy penalty related to the usage of CCS (i.e., to produce 1kWh from coal, more coal is required by the process to power the CCS), which corresponds to 10% according to Bauer et al. (2008). Further, we assume that the technology implemented for CCS is the aforementioned MEA scrubbing, having a 90% effectiveness in absorption of CO_2, NO_x and SO_2 (ETC, 2022).

While for electricity, space heat and district heat the general GECO 2023 mix is used, data for industrial heat is sector specific. Therefore, data for the non-metallic minerals sector are employed, which exhibit a 15% coverage rate for CCS in 2050, mentioned previously. This heat is mainly used in cement and concrete production, whereas the heat for the clinker production was detailed in the precious section. The exact composition of the different types of energy mixes, modelled with Ecoinvent 3.9.1 processes, is provided in **Annex 3.**

4.1.5 Sensitivity analysis

The sensitivity analysis is focused on the assumption made on the energy mixes and energy efficiency improvements. The GECO 2023 (Keramidas et al., 2023) provides three different scenarios, namely a Reference scenario, the NDC-LTS scenario, and the 1.5°C scenario. The assumption made in the default case (i.e. using the NDC-LTS scenario for the projections) is challenged against considering the energy mixes calculated under the Reference scenario conditions. The reference scenario models a world where only policies (and their corresponding targets) legislated as of June 2023 are considered. This implies that future policy targets and respective action plans, whether legislated or not, are not necessarily reached (Keramidas et al., 2023). Therefore, the energy mix is overall less ‘green’ and the application of CCS is limited. Additionally, it is assumed that the composition of the alternative fuel mix for the clinker production maintains the composition of 2020 with a share of 52% alternative fuels and is not increased to 95% in line with CEMBUREAU’s projections (2024b). Finally, the energy efficiency of the cement kiln is also held constant, in contrast to the projected energy efficiency improvements projected by Georgiades et al. (2023). Moreover, CCS is not implemented at the cement plants (reducing the implementation rate from 25 to 0%). The collection of these decarbonisation assumptions presents the results that would be achieved, if decarbonisation would advance less than expected.

4.2 Methodology LCC

The life cycle costing is performed following state-of-the art approaches as detailed in Hunkeler et al. (2008) and Martinez-Sanchez et al. (2015). The LCC shares the same goal, scope, system boundaries and functional unit as the LCA.

In an LCC, two types of costs are accounted for, namely internal and external costs (or externalities). Internal costs include production and management costs (i.e. costs incurred by the different actors in the supply chain), usually distinguishing between operating and capital costs (OPEX and CAPEX). They also cover transfers (i.e. taxes, subsidies, fees, and value added tax) which represents a re-distribution of capital amongst the different stakeholders in the system. In contrast, external costs are non-monetary transactions reflecting the shadow prices of the emissions. While there are several ways to monetarise the damage costs of emissions, they are herein estimated in line with De Bruyn et al. (2018). They cover prices for emissions to air/soil/water, but not for other disamenities, such as noise, odour, accidents, or others.

Two types of LCC are distinguished based on the definition provided in Hoogmartens et al. (2014), namely the *environmental* LCC (eLCC) and the *full environmental* LCC (feLCC)[2]. The former includes all internal costs, while the latter accounts for the monetarised environmental emissions from the 16 impact categories assessed, which are currently not internalised in the internal costs. Note that one needs to be careful with transfers in a feLCC. If the transfers already cover the entire external costs, then they should not be included to avoid double-counting, given the environmental externalities are already accounted for. Finally, costs and externalities occurring in the future are not corrected for inflation to ensure consistency with the LCA and thus expressed as EUR2022.

On top of the 16 environmental indicators, the eLCC and feLCC also quantify employment as an additional impact category. The impacts related to job creation are estimated following the methodology reported in Taelman et al. (2020), while cost of labour is included as an operational expenditure in both the eLCC and the feLCC. The underlying inventory data may be consulted in **Annex 3**.

4.3 Epistemic uncertainty of alternative socio-economic futures

With the current design of the analysis, there is an underlying assumption that the socio-economic system on which the industrial system is based will not change significantly. It is thus expected, that technological and socio-economic trends will continue as per the historical trajectory. Taking an anticipatory governance approach, it is essential to understand that the current reality might develop in radically different ways, subjecting the present analysis and its results to substantial epistemic uncertainty (Langkau et al., 2023). One way to address these is the use of alternative socio-economic scenarios which can be predictive, explorative or normative (Börjeson et al., 2006). A well-known set of scenarios used in integrated assessment models are for example the explorative shared socio-economic pathways scenarios (van Vuuren et al., 2017), for which global data regarding population, GDP growth, inequalities, material flows and related emissions corresponding to different socio-economic development paths are available (Narayan et al., 2023; Schandl et al., 2020; van Beek et al., 2020). Another set of explorative scenarios was proposed by Bauwens et al. (2020) with a 2 x 2 matrix, containing the axes along high-tech and low-tech innovations and the type of governance, being either centralised or decentralised. With a strong focus on technology rather than socio-economic aspects, it needs to be underlined that these four scenarios are more closely related to CE than the Shared socio-economic pathway scenarios. Both scenario sets are, however, explorative scenarios, while for the current analysis, the goal is to identify how the CE can best support the net-zero transition by 2050, requiring a normative scenario approach. Therefore, the Strategic Foresight scenarios and transition pathways for EU 2050, developed by the Policy Lab of the Joint Research Centre were deemed suitable for the current purpose. They allow for the imagination of different futures that all lead to a net-zero transition, though with different socio-economic implications. The scenario of not achieving net zero by 2050 is partially already covered by the previously described sensitivity analysis with the more fossil-based energy mix in Section **4.1.5**.

The normative scenarios by the JRC are separated into a 2x2 matrix with the axes of policy mixes either supportive or not supportive of sustainability and with either a collaborative or competitive outlook on society (Matti et al., 2023). This results in four different background scenarios, into which

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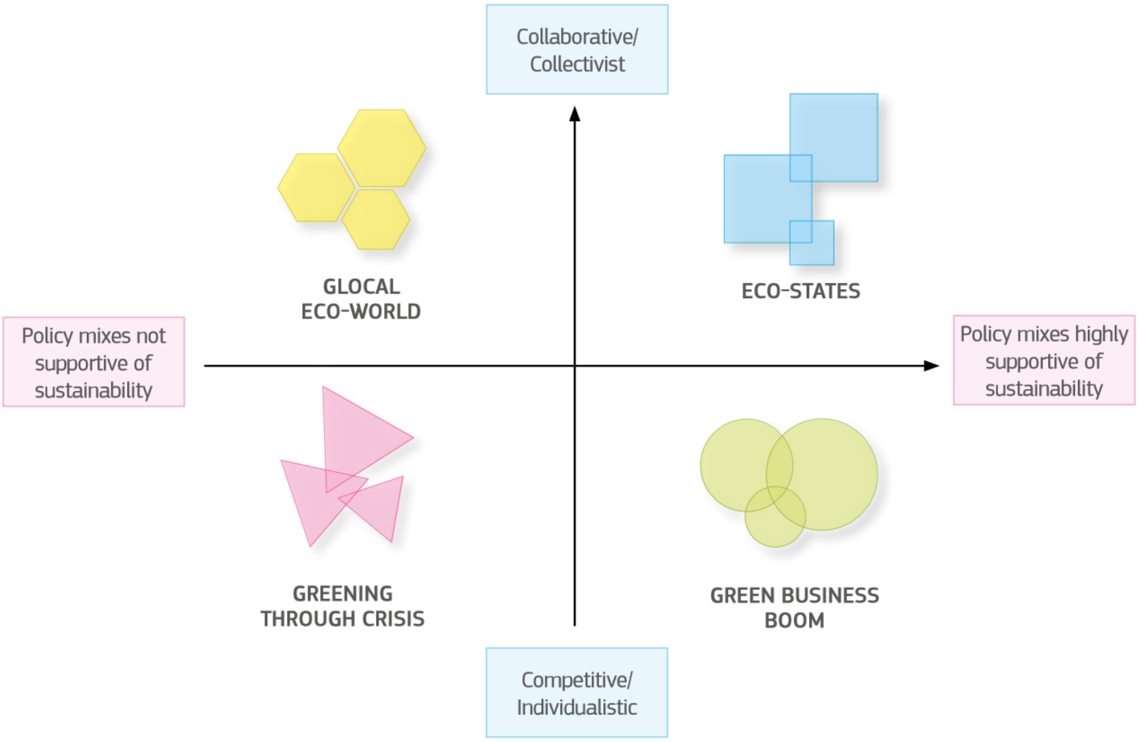
[2] The feLCC has originally been referred to as societal LCC by Hunkeler et al. (2008). It implies a monetarisation of the LCA results, and adds these costs on top of the internal costs.

the current analysis of circularity in the cement and concrete sector will be embedded to address the epistemic uncertainty of the results. It is important to understand that it is not the intention to claim that the future will develop in one way or the other, but rather to show different ways *how* the future could develop and to see how the ambitious circularity scenario would fare in these different futures. This is attempted by estimating the effectiveness of the CE levers in the different scenarios, while taking into account the characterising background conditions. While it is not the goal to create exact predictions of how CE policy will materialise in the four different worlds, understanding their main drivers and actors can support reflections around the implementation of the CE levers. This will enable policy makers to take more informed decisions, by pushing the thinking towards implications of circularity levers that are beyond current realities (Muiderman et al., 2020). The following paragraphs will describe the main characteristics of the four scenarios, depicted in **Figure 11**.

Figure 11. Four scenarios leading towards a sustainable Europe 2050



Source: Matti et al. (2023, p. 101)

4.3.1 Glocal Eco-World

In a Glocal Eco-World, there is an overall demand reduction because of a shrinking economy with strong local actors. Given the limited power of national actors, fiscal resource and related state investment in research and development as well as public infrastructure are limited. This makes large-scale efforts of e.g. investing in recycling capacity more challenging. Service-based business models have a high uptake due to collaborative mindset of people. There is a strong sense of duty to act sustainably and therefore an intrinsic motivation to engage in circular behaviour such as re-use or recycling. There is a focus on resilience, strategic autonomy and sufficiency. The economy is generally oriented towards local markets with short supply chain and trade with China is diminishing. Instead, the EU trades with likeminded partners.

4.3.2 Eco-states

In an Eco-states scenario, there are strong national governments with cohesive policy mixes towards more sustainability, leading to economic growth with limited resource use increase. Given the high fiscal power, there is high tax income and thus investment in green technology and innovation by the state. This entails a digital infrastructure, facilitating tools such as the digital product passport and communication through virtual platforms. As energy prices are set on EU level, industries are forced to save resources through stringent requirements on recycling, reuse and repair of goods. Given the utilitarian outlook of citizens with a focus on compliance, people conform to sustainable lifestyles promoted by governments and engage in individual and sharing CE practices. The global world order remains similar to the one of today with multilateralism continuing.

4.3.3 Greening through Crisis

In a world that is Greening through Crisis, CE is a survival strategy and serves as a means to achieve strategic autonomy and to deal with resource scarcity. The overall economy is shrinking, requiring efficient resource use. Investment is limited to strategic independence, thus supporting the reshoring of manufacturing and increasing the importance of the local industry. There is ample public private partnership for innovation and technology made in the EU, given the low fiscal power of the EU itself and somewhat larger power of Member States. Policy coordination and standardisation across the EU is limited making the scaling of technologies and sharing business models more challenging. Overall, the citizens have limited trust in the EU and are focused on survival rather than the collective good. Trade policies have become more protectionist, increasingly imposing tariffs, and multilateralism has deteriorated.

4.3.4 Green Business Boom

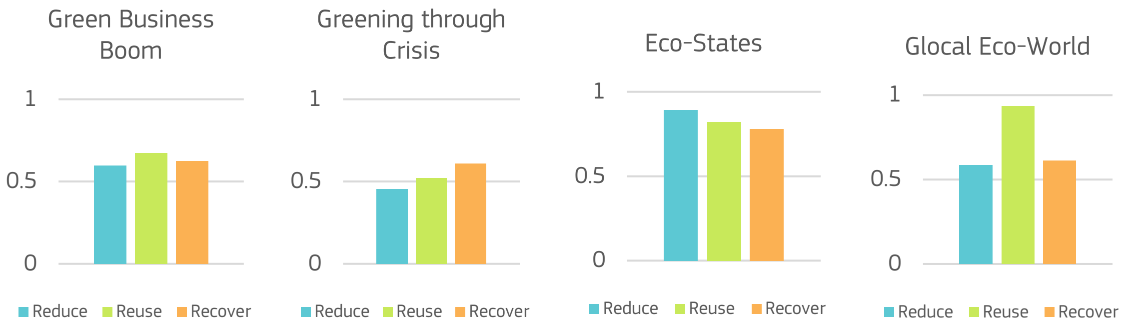
In the case of a Green Business Boom, international corporations are the main actors, taking their decisions in a framework of carefully designed incentives towards sustainability. Both investment and innovation are high and led by business. There is a green fiscal framework on EU level creating tax income and the economy overall is growing. As resource decoupling is limited, carbon capture plays an important role in the energy transition in addition to CE practices. The way CE R-strategies are proliferated is through standards and monitoring procedures. There is a focus on improved resource efficiency and waste recirculation, as they are considered resources. Citizens are acting according to individualist incentives, with sustainable behaviour mainly steered by price, rather than intrinsic motivation. In an attempt to become more resilient and efficient, the EU is in competition for raw materials and initiates strategic trade cooperation with selected countries.

4.3.5 Participatory evaluation of alternative socio-economic futures

Given the inherent epistemic uncertainty of the future, the LCA and LCC are supplemented by a sensitivity analysis based on the “European Strategic Foresight scenarios and transition pathways for EU 2050”. To quantify the narratives underlying these scenarios for 2050, a participatory modelling approach with the inclusion of stakeholders is taken, merging the fields of foresight and prospective LCA (Bisinella et al., 2021; Langkau et al., 2023). This approach yielded i) quantitative estimates on the effectiveness of selected CE levers under different socio-economic scenarios, and ii) key background variables related to future scenarios.

The adaptation of the background system is in line with the description of the scenarios themselves, supported by expert consultation, while the effectiveness of the circularity levers in those scenarios was established through a participatory workshop as proposed by Langkau et al. (2023). This workshop was conducted to test the impact of the four different socio-economic futures on the effectiveness of the implementation of circularity levers in the cement and concrete sector. During the 3h interactive online workshop, ten experts had to rate the effectiveness of the circularity levers on a scale of 1 to 7, categorised into “reduce”, “reuse” and “recover”, within the respective scenarios. Moreover, the participants added comments on sticky-notes onto a shared digital board, contextualising the scoring. The resulting effectiveness of the levers is then used in the sensitivity analysis, by correcting the default effectiveness value of the levers obtained from literature with the one established in the workshop. Indeed, we observed that the majority of studies implicitly assume a 100% effectiveness of CE levers, without considering external factors besides the energy transition (Material Economics, 2018, 2019; Nilsson et al., 2020; Zibell et al., 2022). After the workshop, a sense-making session with a subset (6) of the workshop participants helped to determine the values for the background variables pertaining to the scenarios, such as general demand increase in the economy.

Figure 12. Impact of circular economy clusters on material flows



Note: Material flows are normalised to scale 0-1 (0 = low effectiveness, 1 = high effectiveness)

Source: JRC elaboration

Figure 12 shows that levers related to reduction have the highest effectiveness in a scenario with strong government (Eco-States), whereas reuse levers are expected to function the best in scenarios with strong compliance (eco-states) or sustainability awareness (Glocal Eco-World) of citizens. The recovery of cement and concrete is most effective where centrally supported by state legislation (Eco-States). In accordance with the sense-making session following the workshop, the obtained effectiveness factors will be separated into the ranges low (45-59%), medium (60-74%) and high (75-89%). As for the second objective (testing background conditions), the participatory approach suggested to scale demand for cement and concrete to the size of the general economy in the respective scenario, with numerical values inspired by the quantification of integrated assessment models such as the shared socio-economic pathways (Narayan et al., 2023; Schandl et al., 2020). It was also decided to use rather extreme values to depict these scenarios, as to assure a notable effect in a caricaturising manner. The final numbers for both the lever effectiveness and background adaptations for the LCA are presented in **Annex 4**.

4.4 Results

Whereas results are available for all 16 impact categories of the PEF methodology and different cost categories, only a subset of them are presented here. The rest are documented in **Appendix 5**. For Secondary Material and the Circular Material Use Rate (CMUR), the mass of recirculated material substituting the virgin counterpart is represented as a positive value. In the results for Climate Change, and Environmental Life Cycle Costs, positive values represent a burden for the environment or a cost for the economy, while negative results reflect savings for the environment or economic revenues. Furthermore, the results obtained for Climate Change relative to the sensitivity analyses performed on energy mixes (section 4.4.5) are also discussed. As to account for the different impacts of the individual levers as well as their joint impact of either entire CE clusters, or all levers, the results are presented in a disaggregated way.

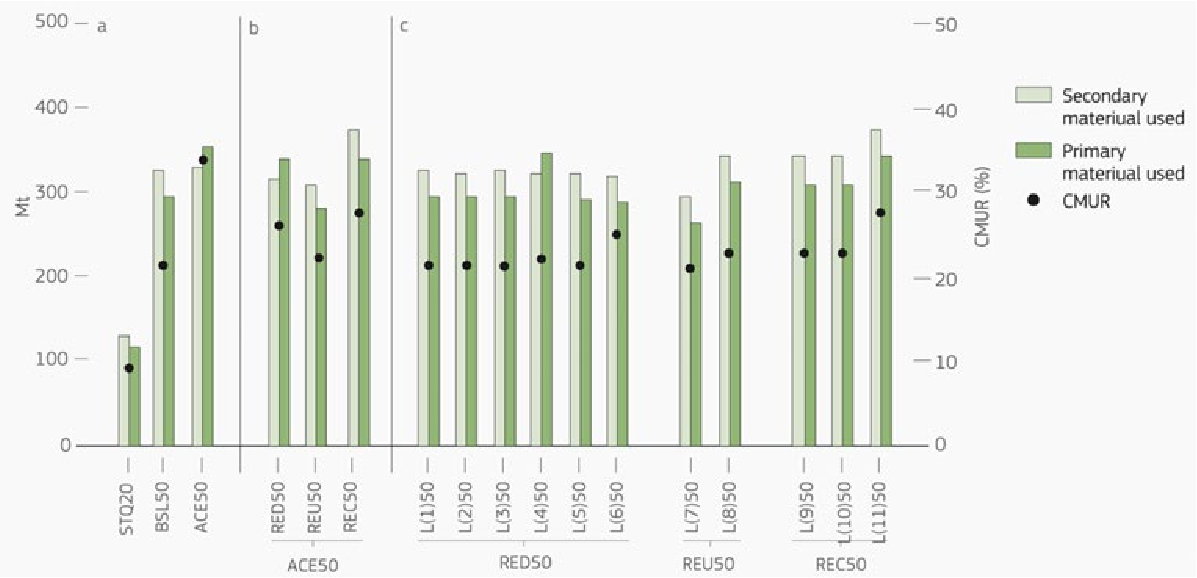
4.4.1 Material circularity: Secondary material use and circular material use rate

The results obtained for the secondary material use expressed as Mt per entire system and the CMUR are displayed in **Figure 13**. The net result obtained for BSL50 equals 323 Mt per entire system, which is 153% higher with respect to the total net result obtained for STQ20. About 138% of this raise is, on the one hand, attributable to the increased recycling, stemming from a higher share of selective demolition and therefore more end of life concrete undergoing either the wet recycling or the ADR process. On the other, the material system also has more inflows, given the higher cement and concrete demand, accounting for the remainder of the increase. The CMUR is expected to increase from 9% to 21% between 2020 and 2050, mainly due to the increased ratio between material inflow and outflow (from 11% to 27%).

The bars representing L1-L11 depict the material flows when individual levers are applied to the BSL50. Their effect is clustered in reduce, reuse and recover, with an aggregation in the ACE50 scenario. The results obtained from the ACE50 span from 292 (i.e. L7 Lifetime extension) to 373 (i.e. L11 Recycling to concrete) Mt per entire system. Taking into account the CMUR, L11 leads to the highest increase at 28%, due to increased recycling, with other notable levers being L6 (25%), both related to the reduction of concrete demand. The reduce cluster (L1-L6) results in a decrease of 2% relative to the BSL50, mainly due to L4 and L6, reducing the overall material demand (in the case of L4 substituted with wood). While L5 also decreased the demand for cement, the reduction is a lot lower in terms of mass and thus less notable. L1 to L3, all substitution levers, are not affected, as the secondary material used for substituting clinker and cement is taken from other material cycles and thus not accounted for. Given the demand reduction, this also is the CE cluster with significant CMUR increase, to 26%. For the reuse cluster levers (L7 and L8), secondary material use is reduced by 4% because of L7 Lifetime extension, lowering the material inflows and outflows. The CMUR stays almost constant in this case, as the demand decrease and recycling decrease are cancelling each other out. In contrast, the combined effect of the levers of the recover cluster leads to an increase in the net result of almost 15% relative to the BSL50 value. Whereas the increases for L9 and L10 are around 6%, given the lower capacity of advanced recycling techniques, L11 yields a 15% increase in material recycled through the more extensive use of existing technologies. As expected, this CE cluster leads to a slight increase of the CMUR to 28%, attributable mainly to L11.

The implementation of all levers simultaneously (i.e. ‘All levers’ in **Figure 13**) results in a 1% increase relative to the BSL50. The reduction in the mass of recycled concrete is mainly affected by the reduce cluster and recover cluster, though the effect of this reduction is partially subject to temporal delay, given the long lifetime of built structures. Moreover, a look at the CMUR, with a positive difference of 13% between the BSL50 and the ACE50 further shows how the decrease in demand (mainly through the reduce cluster) can be a significant driver to improve this metric. Finally, it is essential to keep in mind that in the case of concrete, the weight of recycled concrete is not as important as the type of final recyclate. Indeed, having lower amounts of recycled cement fines (replacing e.g. clinker raw materials) can yield higher environmental benefits than aiming for maximising the mass of recycled aggregates, as most of the energy is used in the production of clinker, not primary aggregates.

Figure 13. Results of secondary material use in Mt and circular material use rate (CMUR) per entire system



Source: JRC elaboration

4.4.2 Climate Change

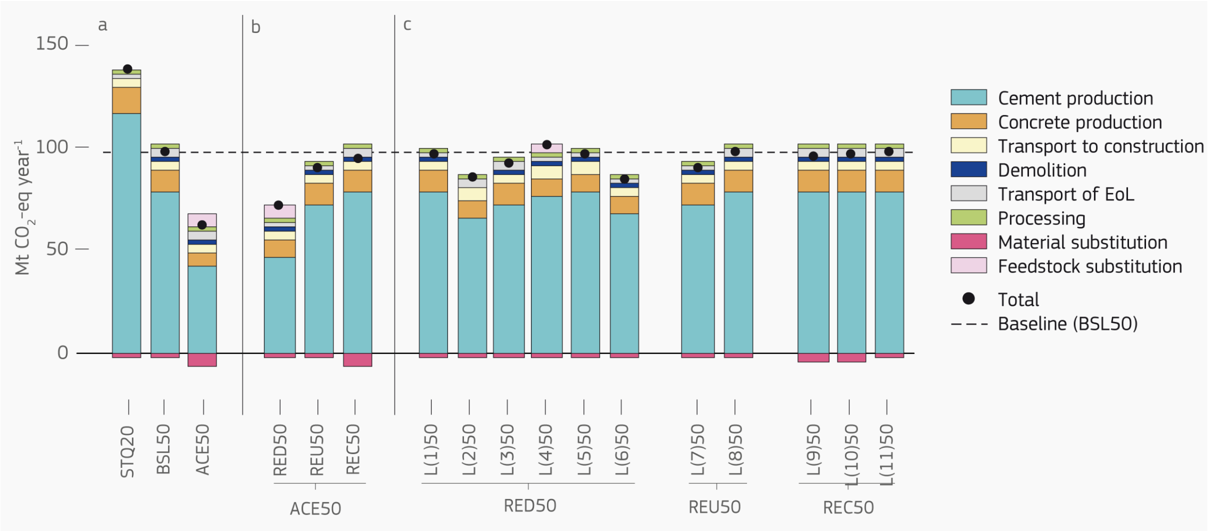
The results obtained for Climate Change expressed as million tonnes of CO_2 equivalents (Mt CO_2-eq.) per entire system are displayed in **Figure 14**. The net result of the BSL50 corresponds to 100 Mt CO_2-eq. per entire system, which is 28% lower with respect to STQ20. The reason for this is that despite of the production increase of cement and concrete in EU, the emissions related to production decrease as a consequence of the decarbonisation of the energy mixes. Without the production increase, thus only focusing on decarbonisation, the reduction would be as high as 32%. Moreover, a higher level of recycling enables more material substitution, further lowering the result.

The net results obtained in the ACE50 span from 61 (i.e. All levers) to 103 (i.e. L4 concrete substitution) Mt CO_2-eq. per entire system. Levers related to the reduce cluster, i.e. levers 1-6, show the largest potential for decreasing environmental impacts (-28%), though the magnitudes vary significantly. For instance, Lever 1 on raw material substitution through ashes from co-processing shows -1% improvement with regards to the BSL, while concrete reduction through more efficient design and following of building standards yields a 14% reduction. The only lever resulting in overall negative impact of 3% on the scenario is L4 Concrete substitution through timber, because the reduction of concrete does not offset the additional emissions created by the timer lifecycle. Given the long lifetimes of the built structures, the end of life is not affected by reduction levers, meaning that the absolute amount of recovery is identical to the BSL50. The levers related to the reuse cluster correspond to L7 and L8; when these are implemented simultaneously, they result in a net reduction of 8% relative to the BSL50 scenario. The large majority of this reduction is due to L7 Lifetime extension, reducing the demand for construction while simultaneously decreasing demolition, though to a lower degree. In contrast, the contribution of L8 Concrete reuse is <1%, as only 18% of the demolished concrete is deemed reusable, and only a fraction of it (10%) is actually reused. However, the L8 Concrete reuse accounts for more material substitution, as visible in **Figure 14**. The levers related to the recovery cluster correspond to L9-L11. When implemented simultaneously, the reduction with respect to BSL50 is 3%, being the smallest reduction of all three CE clusters. Both lever L9 and L10 correspond to replacing virgin clinker raw material and cement, respectively, with recycled cement fines. The net reduction is between 1-3% because of the energy use for the recycling process, which, in the case of HAS is still energy intensive. For L11, existing recycling technologies are used more extensively to produce recycled concrete aggregates, replacing gravel and sand. In contrast to L9 and L10, the increased impacts from selective demolition and recycling do not compensate for the emission savings from material substitution.

The implementation of all levers simultaneously (i.e. 'All levers' in **Figure 14**) results in a reduction of 38% relative to the BSL50 scenario. Given the structure of the material flows, it becomes evident that rather than focusing on recirculation of resources, demand-based levers based on substitution and reduction result in the highest environmental savings. As long as the material inflow into the construction sector is more than four times the weight of material outflow, it will be impossible to replace all virgin material, even when recirculating most of the material at end of life. The reduction in the final demand of products (i.e. concrete) has the greatest potential in reducing the burdens of production, which are further reduced by the lever related to the reuse cluster. However, increasing the limited capacity of HAS or other technologies allowing for the recycling of cement fines to new clinker raw materials or cement replacement, bears sizeable impact reduction potential.

If the demand for cement and concrete remains high and grows as projected, the decarbonisation of the energy grid will not be sufficient to have a net-zero, or, close to net-zero, sector by 2050. The results of this analysis show that CE levers can contribute a significant part to the solution. Whereas the general discourse on CE in policy has to date been focusing on the end of life levers, related to recirculation of materials, the results depicted in **Figure 14** show that the greatest potential for reducing Climate Change impacts is related to a reduction in demand for products.

Figure 14. Results of Climate Change in Mt CO_2-eq. per entire system



Source: JRC elaboration

4.4.3 Remaining impact categories

Whereas several of the impact categories are following the trends of climate change (i.e. ozone depletion, ionising radiation, eutrophication – freshwater, resource use - energy carriers), there are also instances where the BSL50 already starts higher than the STQ20 (i.e. human toxicity – carcinogenic & non-carcinogenic, particulate matter, photochemical ozone formation, acidification, eutrophication – terrestrial & marine, ecotoxicity, land use, water use, resource use – materials & minerals). This implies that the higher material demand in 2050 is not offset by a cleaner energy mix, or a change in the end-of-life treatment of concrete waste. In all categories, except for land use and particulate matter, the STQ20 impacts are higher than in the ACE50 impacts. The reason why there is an increase, especially for land use, is (again) L4 Concrete substitution with timber, due to the more extensive use of land to cultivate the trees. It also holds that in most of the remaining impact categories, the omission of L4 leads to higher reduction potentials in the ACE50, with differences up to 50% (i.e. eutrophication – freshwater). In terms of processes contributing to the impacts, it is noteworthy that in almost all impact categories except for climate change and the environmental costs, the impact of the concrete production is similar to that of cement production. This stems from the aggregates production, involving quarrying, which is powered by diesel combustion. While electric mining trucks do exist and their use is expected to increase, their deployment by 2050 has not been taken into account, given the focus of the study is on circularity and not on decarbonisation. These impacts (which are potentially overestimated) are especially noteworthy for impact categories related to ozone depletion and human toxicity as well as eutrophication, due to the high emissions of NO_x, SO_x and particulate matter (Miller & Moore, 2020). The detailed results of the remaining impact categories are provided in **Annex 5**.

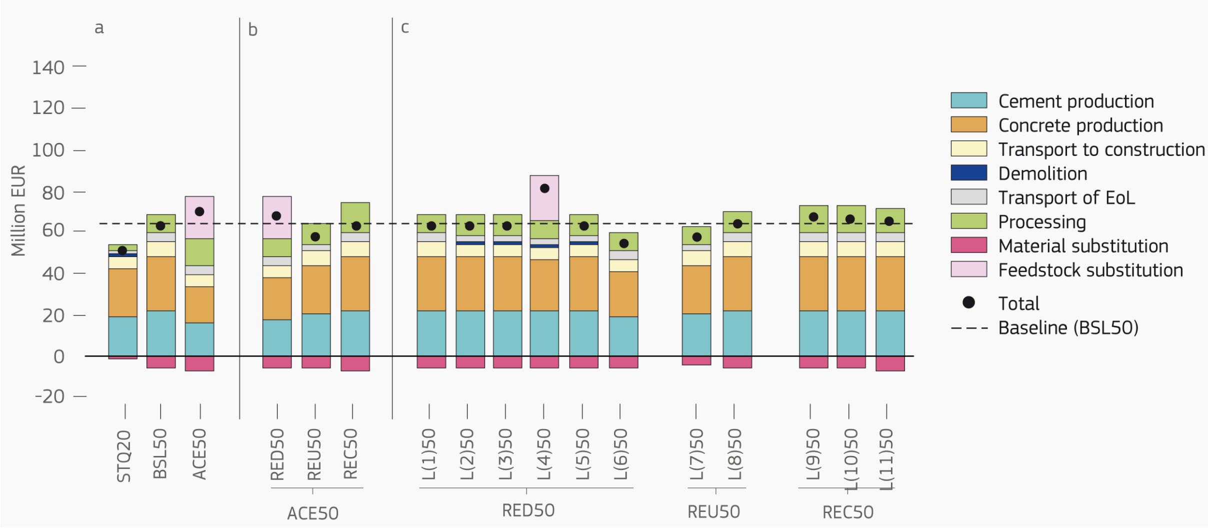
4.4.4 Life Cycle Costs

The results obtained for the Environmental Life Cycle Cost (eLCC) expressed as EUR billion per entire system are displayed in **Figure 15**. The net result of the BSL50 equals EUR 63 billion per entire system, which is 23% higher than the net result obtained for STQ20. In comparison to 2020, processing costs at the end of life from the recycling process are higher than the additional revenues generated through material substitution, accounting for 52% of the cost increase. In combination with increased cement production, the environmental lifecycle costs are thus above the values for 2020.

The net results obtained from the ACE50 span from EUR 55 (i.e. L6 Concrete reduction) to 82 (i.e. L4 Concrete substitution) billion per entire system. Whereas all in all, the trend observed for Climate Change is reflected in the eLCC results, the implementation of L4 in both the reduce cluster of inputs and the ACE scenario is distorting the results. The reduce cluster levers (i.e. L1-L6) generate a 14% cost increase relative to the BS50. As mentioned previously, the reason for this is that there are no cost savings through clinker (L1 and L2) and cement substitution (L 3), and concrete substitution (L 4) involves even higher costs (+29%). Only L5 and L6, being cement and concrete reduction, respectively, can reduce costs in production. However, these might be offset by additional costs not considered for required changes in the building designs and replanning. Excluding L4 Concrete substitution through timber from the reduce cluster results in that CE cluster having the greatest potential in reducing production costs (-15%). With regards to the reuse cluster, a cost reduction of about 7% with regards to the BSL is expected. Given the reduction in construction and demolition related to L7 Lifetime extension, a 8% reduction is expected, while L8 Concrete reuse has the potential to increase costs by 1%. This is mainly due to additional costs related to handling and transporting the concrete to be reused. Considering the recovery levers (L9-L11), again, a 8% cost increase is expected due to the relatively high processing costs, not offsetting the revenues from the material substitution. The levers replacing either clinker raw material (L9) or cement (L10) incur a cost increase between 5-7% due to the higher use of the ADR and HAS technology, whereas the recovery of concrete aggregates (L11) to replace gravel and sand implies a raise of 4%. This shows that there is a limited price incentive to opt for recycled cement fines and concrete aggregates at the moment.

The implementation of all levers simultaneously (i.e. 'All levers' in **Figure 15** results in a price increase of 11% relative to the BSL scenario. Excluding L4 Concrete substitution through timber from the ACE scenario would result in a 18% reduction of costs instead. Revenues from material substitution are only minimal and cannot offset the price increase of additional processing costs, as visible in **Figure 15**. Finally, it is important to underline that this static analysis is projecting the current resource prices into the future, thus not taking into account price changes related to supply scarcity or energy price increases in the light of carbon accounting. Therefore, a complementary top-down analysis including these price changes is essential for taking meaningful conclusions from the LCC results.

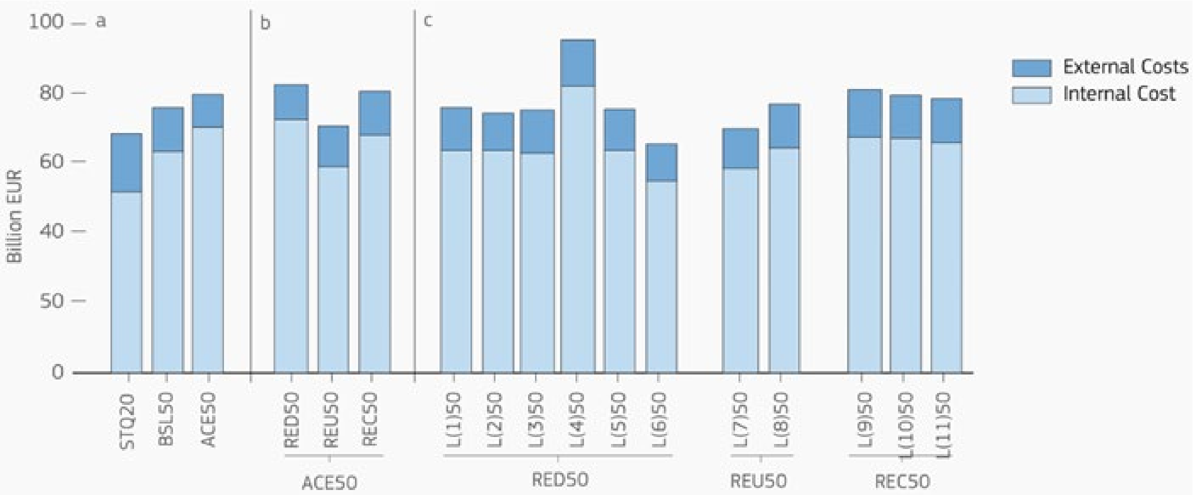
Figure 15. Results of Environmental Life Cycle Cost in EUR billion per entire system



Source: JRC elaboration

The cost of the full environmental lifecycle costs (feLCC), further accounting for the shadow prices of environmental impacts, follows the same pattern as the eLCC. **Figure 16** shows that main difference is that costs are between 16-20% higher, where externalities are also included.

Figure 16. Results of full environmental Life Cycle Costs in EUR billion per entire system



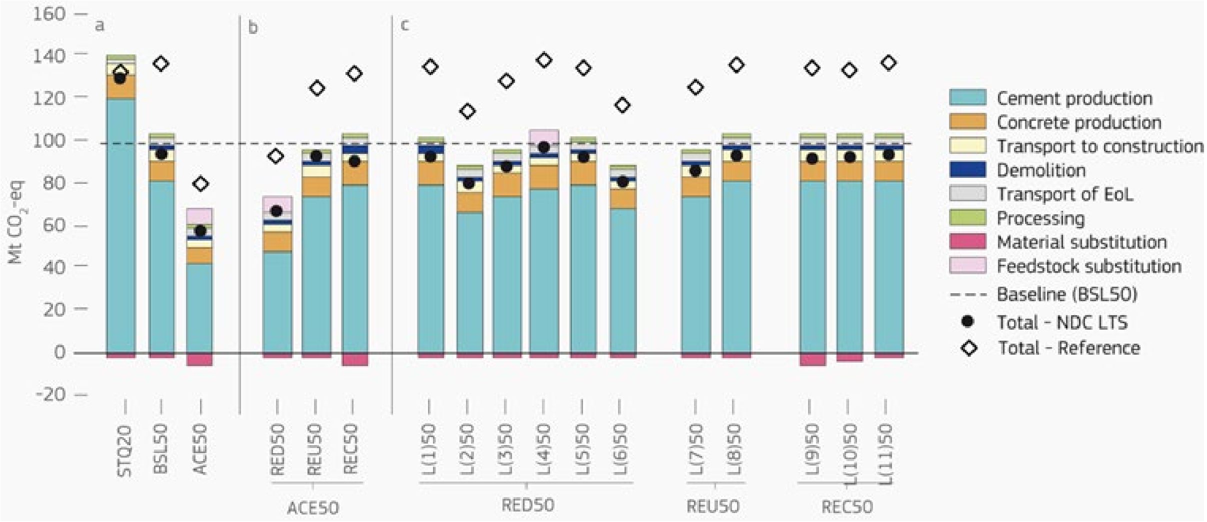
Source: JRC elaboration

4.4.5 Sensitivity analysis: Energy mixes

The sensitivity analysis of the energy mixes compares the GECO NDC-LTS scenario with the GECO Reference (REF) scenario (Keramidas et al. (2023). Besides a lower share of renewable energy, the latter is characterised by lower kiln efficiency and absence of CCS implementation. The results obtained for the Climate Change impact category, indicating the difference of net total values, are displayed in **Figure 17**.

The change between STQ20 and BSL50, when employing the REF energy mix, is positive, increasing by 4%, due to the increase in cement demand and limited decarbonisation. Indeed, the results obtained for the BSL50 are 46% higher when using the REF energy mix than when using the default energy mix. The pattern of the reductions of the different levers follows the one of the default energy mix (between 38% and 48% higher emissions applying the sensitivity). Yet, a notable difference is the 31% decrease from the BSL50 to the reduce cluster using the REF energy mix. In contrast, the jump from the BSL50 to the reduce cluster using the default energy mix is only 28%. The overall decrease from the BSL50 to the ACE50 in the case of the REF energy mix is also higher, at 41%, compared to the 37% reduction in the default energy mix case. This implies that, in case decarbonisation is not taking place as projected, relative impact reduction gains stemming from the implementation of CE levers might even be slightly higher.

Figure 17. Results of sensitivity analysis with different energy mixes for Climate Change in Mt CO_2-eq. per entire system

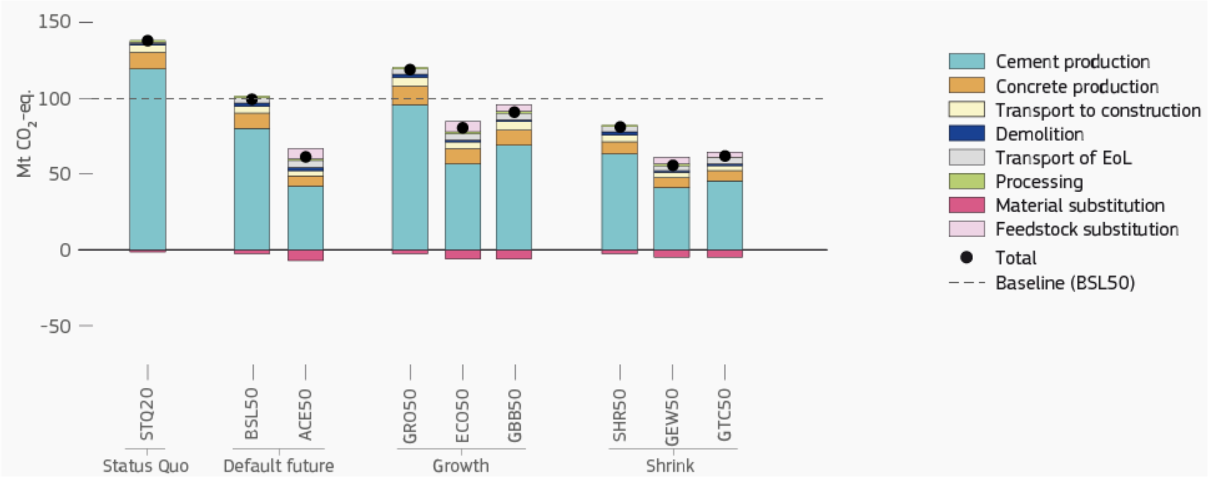


Source: JRC elaboration

4.4.6 Epistemic uncertainty

To analyse how the different types of futures would impact the results of the assessment, the effectiveness of the levers was adapted to the results of the participatory workshop and sensemaking session. In addition, a reflection on the change in a system with higher or lower material flows was analysed. **Figure 18** displays the result assuming changes in material inflows, varying by 40% in total. What can be observed is that the higher growth scenarios (Eco-States and Green Business Boom) result in higher environmental impacts. However, it can also be seen that the higher effectiveness of the levers in the Eco-states future leads to a lower emission increase than the Green Business Boom. For the two degrowth scenarios, the differences are smaller, also given that the system is scaled down, bringing the two futures closer together. Both the Glocal Eco-World and the Greening through Crisis world have impacts that are consistently below the future in line with the historical trajectory and 100% lever effectiveness, due to the material demand decrease. It needs to be pointed out, however, that this difference is narrowing especially for the reduction levers and the ACE50, where the reduced lever efficacy is almost offset by material demand decrease. Yet, those results are specific to the impact category climate change. In most other impact categories, the demand decrease results in the degrowth futures yielding lower impacts than the default scenario with full lever effectiveness. The question remains, whether the two growth scenarios also entail an increase in virgin material flows (as is modelled here), or whether the increased demand stemming from the economic growth can be satisfied by servitisation of materials and increased recycling instead.

Figure 18. Results of epistemic uncertainty on climate change



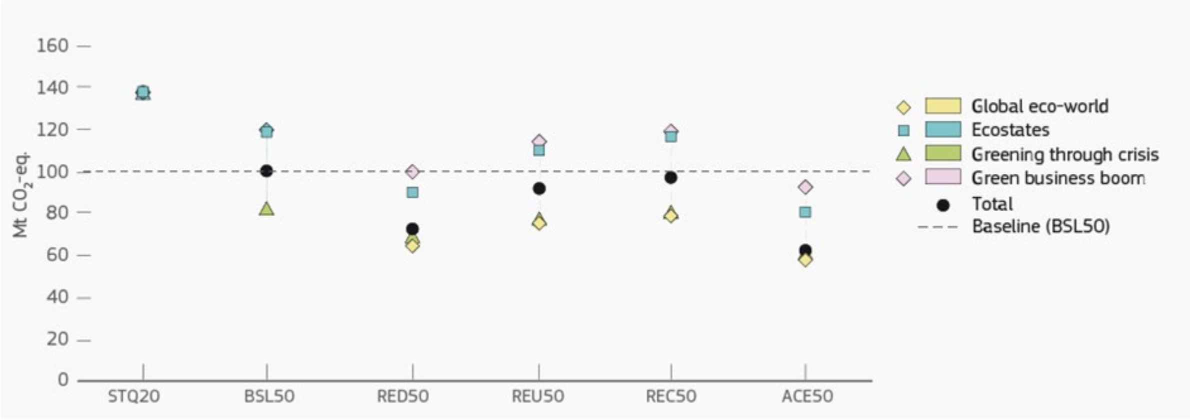
Note: STQ20 stands for the status quo scenario 2020, BSL50 for baseline scenario in 2040, ACE50 for ambitious circular economy scenario 2050, GRO50 for 2050 baseline increased by 20%, ECO50 for Eco-states scenario in 2050, GBB50 for Green Business Boom in 2050, SHR50 for 2050 baseline decreased by 20%, GEW50 for Global Eco-World in 2050 and GTC50 for Greening through Crisis in 2050.

Source: JRC elaboration

It is further observed from the data by CE lever cluster in **Figure 19**, that the results are not sensitive to the socio-economic background scenarios, except for the 'reduce' cluster. The highest discrepancy can be observed in the reduction lever, where the Eco-states scenario is closest to the ideal implementation scenario under a future following socio-economic developments along historical lines. In contrast, the other three futures present higher impacts, given the incomplete implementation of the reduction levers. In the ACE50, it is visible again that a Green Business Boom would lead to the highest emissions with the selected levers, while a world in an Eco-States future fares closest to the standard prediction.

For the interpretation of these results, the important finding is that all four future scenarios are below the BSL50 values. This indicates, that CE levers have a positive effect on climate change irrespective of the socio-economic background scenarios, including the scenarios with significant material demand increase.

Figure 19. Results of epistemic uncertainty analysis on climate change with resolution by CE lever cluster



Source: JRC elaboration

5 Input-output analysis

Whereas the bottom-up assessment provides a high granularity of the material flows and associated impacts, the depiction of the interaction with other industry sectors and countries is limited. Therefore, this section describes Environmentally Extended Multi Region Input Output (EE-MRIO) models, which are well equipped to show the interdependencies between industries and within and between countries as well as between intermediate and final product producers and consumers. The following subsection lines out the methodology and its operationalisation, with a focus on the integration of the bottom-up LCI, the creation of the extension tables as well as the use of the GECO 2023 data for the prospective tables. Thereafter, the results of the analysis will be presented. A more detailed description of the model used here can be found in Wagner et al. (2025).

5.1 Methodology

EE-MRIO models provide a useful toolbox for assessing social, environmental, and economy-wide impacts of both goods and services of the transition towards a more circular economy (Wiebe et al., 2019), avoiding a cut-off on (economic) flows. By incorporating explicit exogenous technological and demand change, it is possible to model direct and indirect effects of demand in a what-if scenario, but not to model the dynamic response of an economy, such as macro-economic price changes or systemic rebound effects (Wiebe et al., 2018). It requires that any induced or rebound effects need to be exogenously included in the modelling. Induced effects refer to secondary economic effects resulting from changes in spending or investments patterns, caused by an initial change in economic activity. This includes shifts in employment levels as well as changes in firms operating surpluses. Referencing the circular flow of income, these effects can have a multiplier effect on the overall economy, amplifying the initial change in economic activity. Circular economy rebound (Zink & Geyer, 2017) refers to unintended environmental impacts that occur because of circular economy interventions.

Modelling CE interventions in an EE-MRIO framework must be understood as a comparison between the status quo (results from the basic model) and a result in which the what-if scenario is achieved (Aguilar-Hernandez et al., 2018). The net effect of circularity interventions can be quantified by the difference between the two (i.e., BSL50 and the ACE50). Exogenous changes can be applied either in the supply and use tables (e.g., Aguilar-Hernandez et al., 2018; Wiebe et al., 2018; Wiebe et al. 2019) or directly in the input-output tables (e.g., Donati et al., 2020). It is preferred to model exogenous changes in the supply and use table system and to ensure the monetary balance is kept. An IO table is generated from these supply and use tables to allow for typical IO analysis.

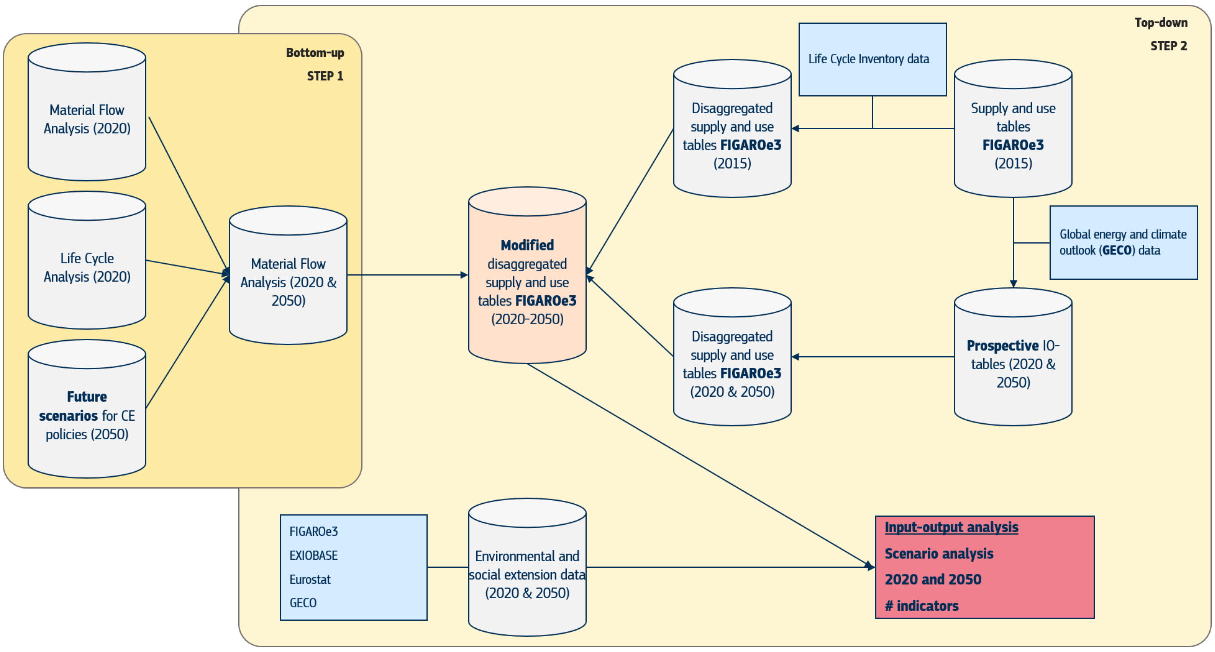
A limitation of EE-MRIO models is the partial inclusion of waste flows, as these are not effectively captured by monetary values (Aguilar-Hernandez et al., 2018). However, as this analysis includes a direct link between the MFA and the IO analysis, we are using a mass balance to understand effects across the production network. So, to overcome the aggregation error of IO tables, a disaggregation of products and sectors in supply and use tables and/or IO tables in more detailed categories provides a solution. Caution is required when assigning circularity in the future. Due to the fixing of technical coefficients of a circular economy scenario, the IO analysis does not capture the volume effects on prices as well as price effect on the use of certain products (Aguilar-Hernandez, 2018). The assessment of prospective impacts relies on exogenous scenarios, where the choice was aligned with the previous modelling in the LCA and LCC. Therefore, the Global Energy and Climate Outlook (GECO) was chosen due to the comprehensiveness of the provided information that exceeds GDP, population, and the composition of the energy sector by providing a complete prospective input-output structure for a long-term baseline scenario based on the computable general equilibrium

(CGE) model GEM-E3. The monetary tables are supplemented with extension tables covering the environmental and socio-economic impacts. While several IO models exist, the Figaroe3 database, with a comprehensive inter-country supply, use, and input-output database for 2015, featuring labour and environmental extensions that are in line with official statistics was chosen (Cazcarro et al., 2025). The database encompasses data for 213 products and 176 industries across 45 geographical areas (country disaggregation is equal to FIGARO), as well as one aggregated rest of the world region. The selection criteria as well as a comparison to other IO models are presented in Annex 6. A more detailed description of Figaroe3's structure, i.e. the monetary supply and use tables, is presented in Annex 7. The IO model uses environmentally extended industry-by-industry tables, of which the Leontief inverse is made assuming consistent input structure for products and industries. To each unit of output, a respective impact coefficient is associated, enabling the assessment of sustainability impacts on to of resource use. The scope includes both indirect and direct impacts/resource use, resulting in the total impacts of the EU-27 and non-EU final demand. The indirect use covers upstream impacts, while the direct use entails impacts directly generated by households. The detailed formulas for these calculations are available in **Annex 8**.

5.1.1 Bottom-up LCI integration

The workflow is visualised **Figure 20** and directly makes use of the material flows and stocks as determined in the MFA. In addition, the details from the LCI-datasets of different processes are used to disaggregate the supply and use tables in order to improve the granularity and quality of the input-output assessment. An application of the methodology and more details on the individual steps is elaborated in **Annex 9**.

Figure 20. Workflow from Material Flow Analysis to (prospective) Input-Output Analysis



Source: JRC elaboration

The first part includes an inspection and preparation of the FIGAROe3 dataset. The preparation is general, while the inspection is case-specific. The inspection of the aggregated EU27-RoW model allows to track flows of resources, materials, and products (in monetary values). Based on the inspection and the comparison with the results from the MFA, a proposal for sector and product disaggregation is made, which in this case, concern the Cement, lime and plaster (CPA_C23_E) and Ash for treatment, Re-processing of ash into clinker (CPA_C23_F) products. After the preparation, the MFA-results are incorporated into the supply and use framework. Subsequently, the RAS balanced prospective tables based on GECO-data are generated. At this point, the disaggregated supply and use table is generated to increase the granularity of the model specifically for the cement & concrete sector sectors/products. Next, the model is regionally disaggregated again to return to the initial geographical detail of FIGAROe3. Performing the IO analysis starts by creating the necessary (disaggregated) extension tables and by deriving the industry-by-industry IO tables.

5.1.2 Extension tables

Besides the monetary values, the IO analysis also provides insight into environmental and socio-economic indicators. It does so through extension tables, which are based on existing models such as EXIOBASE and official emission statistics, in the case of environmental extensions. Other relevant extensions are financial costs, employment and issues of resource dependency.

5.1.2.1 Environmental extensions

Just as in the LCA, the **Environmental Footprint** (EF) method is used, which includes 16 impact categories of the environmental footprint method. Yet, ionizing radiation and ozone depletion are excluded because emissions related to these impact categories are missing. For the disaggregated sector, the LCIs of the elementary flows are taken directly from the LCA, where available. This is of particular importance where elementary flows are not already present in the model, due to the higher granularity of the disaggregated sectors. Both process emissions and combustion emissions are included based on the LCA inventories, and compounded with the upstream and downstream emissions, the emission coefficients of which are taken from the sources described hereafter. Beylot et al. (2019) make use of 78 elementary flows to estimate 14 out of the 16 environmental impact categories. Our project partners VITO created a matrix of characterisation factors in the ETC/CE project of the Consumption Footprint indicator commissioned by the EEA. They translated the 528 unique environmental extension lines from EXIOBASE v3.8.2 into 14 out of the 16 impact categories of the EF-method requiring a conversion through characterisation factors. The result can also be normalised and weighted into a single factor, as presented in **Annex 10**. A wide coverage of environmental extensions is available from the **EXIOBASE** (currently v3.8.2) dataset. The process of matching the EXIOBASE extension with the EF categorisations is described in **Annex 10**. For impacts like toxicity, however, EXIOBASE includes only a very limited selection of emissions. No information, and thus no extension lines, is available in EXIOBASE to estimate the impact categories ozone depletion and ionising radiation. Another shortcoming of the EXIOBASE is that the end years of the real data in the extension tables vary and are therefore not completely up to date[3]. Therefore, the changes in emissions are only based on output volumes and not actual emission data. Some of these data are complemented by the **Eurostat Air Emissions Accounts (AEA) by NACE Rev. 2 activity,** which include air pollutants and greenhouse gases per sector per geographical area from 1995 until 2022. Note, that the dataset is incomplete due to missing data and unavailable data for non-EU countries. For this reason, only the air pollutants for which the AEA data can be

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[3] The end years of the extension tables are: 2015 for energy, 2019 all greenhouse gases (nonfuel, non-carbon dioxide are now casted from 2018), 2013 for material use, and 2011 for most others, land, and water.

supplemented with the EXIOBASE data are retained (total CO_2, CH_4, N_2O, HFC, PFC, NH_3, NO_X, CO, PM2.5, PM10, and NMVOC).

5.1.2.2 Socio-economic extensions

The extension tables of FIGAROe3 show the generation of value added per sector, disaggregated into 9 categories, which comprise taxes, compensations of employees per skill level and different types of operating surpluses. Employment is based on education or occupation, both disaggregated into male and female as well as low, medium and high-skilled. Finally, the concept of EU's strategic autonomy is operationalised in the domestic extraction and use of strategic metal ores, as per the CRM 2023 list. Thus, the focus for strategic autonomy is on the demand for bauxite/aluminium, copper, nickel, PGM's and other non-ferrous metals.

5.1.3 Prospective input-output tables

For the policies considered for the development of the scenarios in the GECO (2023-edition), the reader is referred to the original publication. The scenarios include energy-related policies in the sectors of energy, power, and transport (incl. aviation and maritime), and GHG-related policies focussing on the ETS and non-ETS sectors for certain emission reduction targets. Economic MRIO tables are available, but only for the GECO Reference scenario. This scenario represents a projection of the world economy without additional decarbonisation policies of the energy system. The MRIO tables are supplemented by energy balances (in physical units) and GHG emissions projections. However, the database also includes economic indicators (e.g., value added), detailed energy, GHG and air pollutant emissions balances for several scenarios of the GECO 2023 report (Reference, NDC-LTS and 1.5°C) for 39 world regions and the EU27. In order to align with the NDC-LTS scenario, multiple datapoints from GECO are used to adapt the FIGAROe3 supply and use tables to reflect future changes. The complete procedure is described in Annex 11. Finally, the change in the extension tables is based on the relative change in the emission intensity. The latter is calculated by dividing the emissions by the value added generated by the sector. The change ratio, often a reduction between 2015 and 2050, is applied to the original emission intensities (for CO_2, CH_4, NH_3, NO_X, $PM_{2.5}$, SO_2, and F-gases). All indicators keep the original intensities in the prospective tables.

5.2 Results

The presented results cover the impact categories climate change, resource dependency (with a focus on imported energy carriers) and value added and employment. The complete list of effects is provided in **Annex 12**. Trade is not discussed, given the linear characteristic of the model and further elaboration on it in the dynamic macro-economic modelling. A key difference to the LCA and LCC results is that in the ACE50 scenario, the levers are all implemented at once through the change in material flows. Therefore, there is no insight in terms of magnitude of impact per CE cluster or individual levers. However, given the EE-MRIO is mainly used to determine sectoral spillovers instead of account for the effects per lever (already covered by the LCA), this level of analysis is justified.

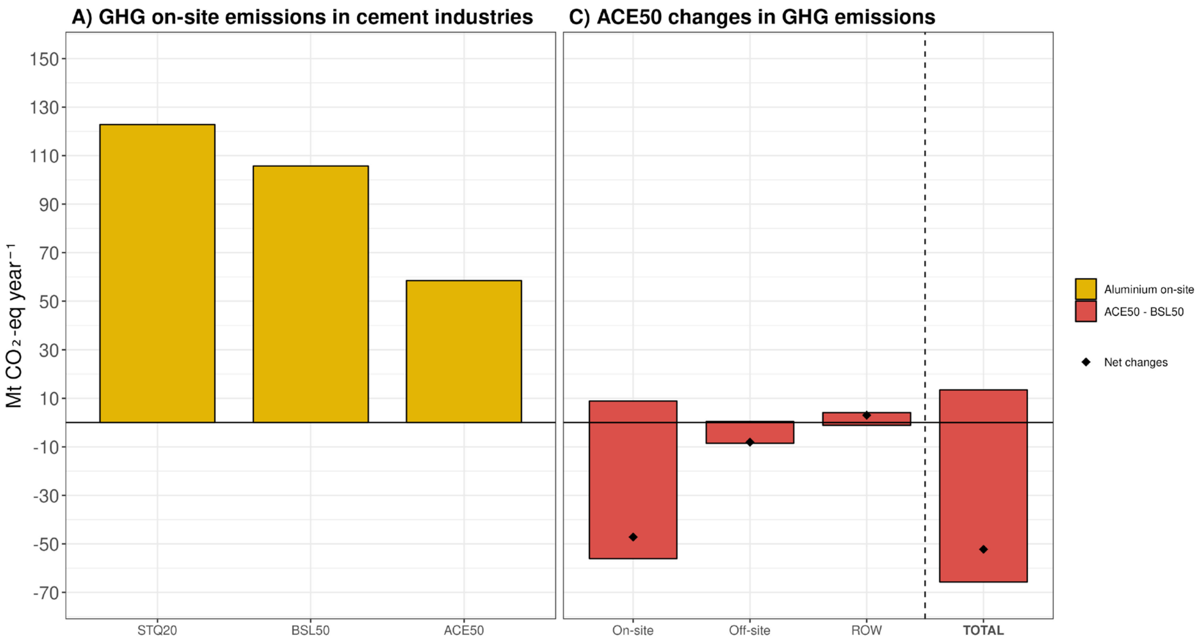
5.2.1 Climate change

Figure 21 presents the Climate Change impacts of four scenarios: Status Quo (STQ20), Baseline (BSL50), and Ambitious Circular Economy scenario (ACE50), measured in million tonnes of CO_2

equivalent (Mt CO_2-eq.). The left-side chart (**Figure 21A**) the on-site emissions[4] in the cement and concrete industry for each scenario. In the STQ20 scenario, emissions total 122.8 Mt CO_2-eq., which decreases by 17.1 Mt CO_2-eq. to 105.7 Mt CO_2-eq. in the BSL50 scenario due to structural changes associated with the green transition. The ACE50 scenario leads to a more pronounced reduction, with a total net reduction of 47.2 Mt CO_2-eq., which represents a 44% decrease of all on-site emis-sions.

Figure 21A only shows total GHG savings in on-site emissions for the cement and concrete industries. To provide insights on total GHG savings, that is, from a supply chain perspective (including e.g. emissions related to inputs used by EU industries), and regardless of where they occur from a geographic perspective (either in EU or in the Rest of the World). **Figure 21B** displays the difference in GHG emissions between the ACE50 and the BSL50 scenarios, while showing the contribution in changes of GHG emissions for on-site emissions in EU, off-site emissions in EU, and imports from the rest of the world (RoW). As shown in **Figure 21B**, burdens (values above the zero line) and savings (values below the zero line) may occur for 'On-site', 'Off-site', and 'ROW' emissions; therefore, the 'Net change' is calculated for each contributor to the final result and for the 'TOTAL' itself. It can be observed that reductions are mainly driven by the decrease in on-site emissions, which account in total for 56 Mt CO_2-eq., and to a lesser extent due to the decrease of 8.5 Mt CO_2-eq. in off-site emissions. The overall emissions savings are partially offset by the introduction of new cement products, such as calcined clay and alternative binders, increasing emissions by 8.9 Mt CO_2-eq., as well as an increase of 4.1 Mt CO_2-eq. in emissions from the RoW.

Figure 21. On-site GHG emissions in cement and concrete industries and changes in total GHG emissions for the ACE50 scenario relative to the BSL50 scenario



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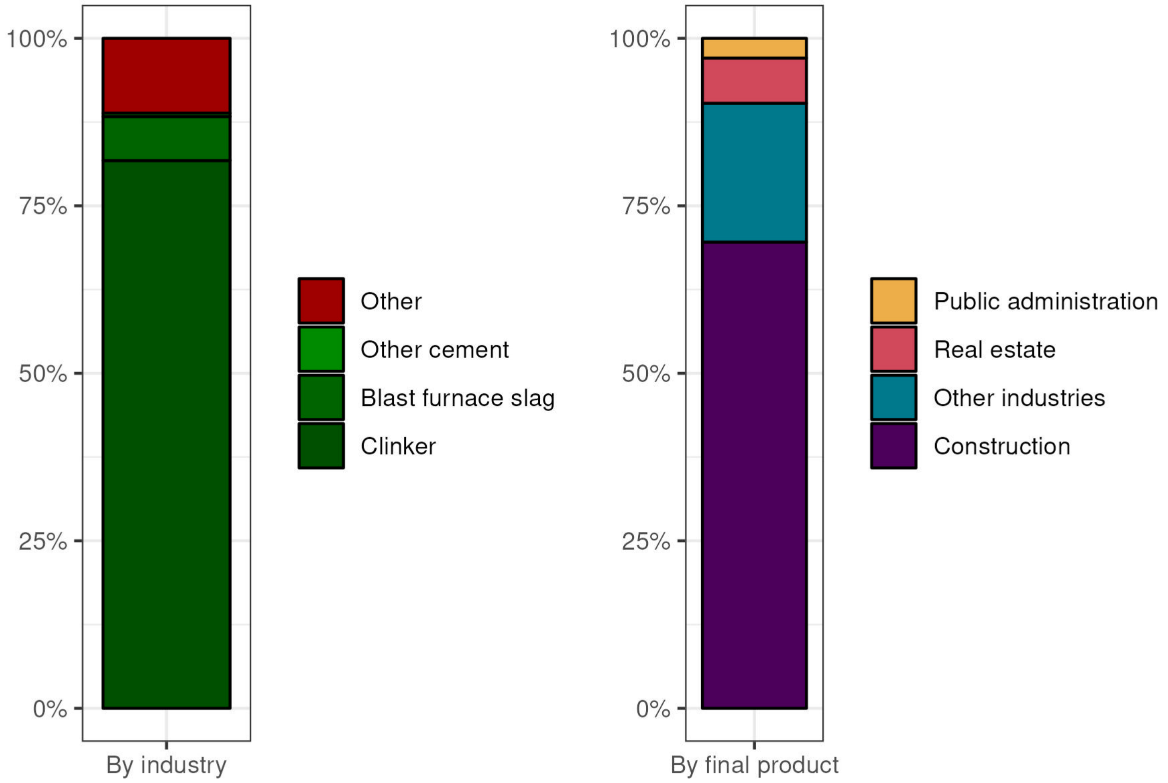
[4] On-site emissions include process and combustion emissions of the cement and concrete industries only.

Note: Panel A) displays the on-site GHG emissions of the EU cement and concrete industry for the Status Quo (STQ20), Baseline (BSL50), and Ambitious Circular Economy (ACE50) scenarios; Panel B) displays the changes in GHG emissions between the ACE50 and BSL50 scenarios (ACE50-BSL50). 'On-site' GHG emissions refer to direct emissions occurring at cement and concrete industries in the EU to satisfy the EU and Rest of the World (RoW)'s demand; 'Off-site' GHG emissions refer to emissions from all other EU industries to satisfy the EU and RoW's demand; 'ROW' GHG emissions refer to emissions occurring in the RoW to satisfy the EU's demand; 'TOTAL' GHG emissions refers to the sum of 'On-site', 'Off-site', and 'ROW' GHG emissions. Notice that the contribution of 'On-site', 'Off-site', and 'ROW' GHG emissions can be a burden (above the zero line) or a saving (below the zero line) for Climate Change. The net change is displayed with a black solid diamond in the figure. All values are expressed as Mt CO_2-eq. year^{-1}.

Source: JRC elaboration

Figure 22 provides insight into the industry, and final products driving these changes. The data reveals that the main activity contributing to these savings is clinker production, accounting for 81.7% of the total reduction, followed by blast furnace slag production with a 6.6% share. The decomposition by final product shows that the construction sector is the primary driver of these changes, responsible for 71.5% of the total savings, followed by services such as real estate activities with 6.8%, and public administration and defence services, compulsory social security services ('Public administration') with 2.9%. The remaining 20.7% savings to balance is spread across other final uses in the economy.

Figure 22. Decomposition of the changes between the ACE50 and the BSL50 scenarios relative to the net reductions in GHG emissions, by industry and final product



Note: The decomposition of the changes refers to net GHG savings as percentage of industry, and final good or service. Only contributions above 5% are shown individually.

Source: JRC elaboration

5.2.2 Resource dependency

Impact on domestic extraction has been minimal, due to the nature of materials used, which are abundant in Europe. Therefore, the analysis focuses here on the energy carriers imported from abroad to sustain EU production. The EEIO model implemented was not specifically designed to assess the impact of energy demand resulting from CE policies. However, as shown in **Table 3**, a rough indication of the changes in purchases of selected energy carriers by comparing the ACE50 and BSL50 scenarios. The results suggest that CE policies have a moderate impact on reducing electricity and heat demand in the EU, with a decrease of approximately 1-1.6% of total region demand. In terms of foreign energy dependencies, the greatest relative and absolute impact is in natural gas. The reductions mainly stem from an overall reduction in the construction sector as well as the cement, lime and plaster sector.

Table 3. Changes in selected products demand in ACE50 in comparison to BSL50.

Selected product	Quantity reduced	Unit	% total EU economy	% EU cement & concrete industry
EU electricity production	-10.1	TWh	-1.6%	-37%
Coal and lignite, extraction of peat	-5.6	PJ	-0.21%	-20%
Crude petroleum	-8.8	PJ	-0.083%	-22%
Natural gas	-37.3	PJ	-0.26%	-27%
Other fossil fuels	-1.1	PJ	-0.23%	-42%

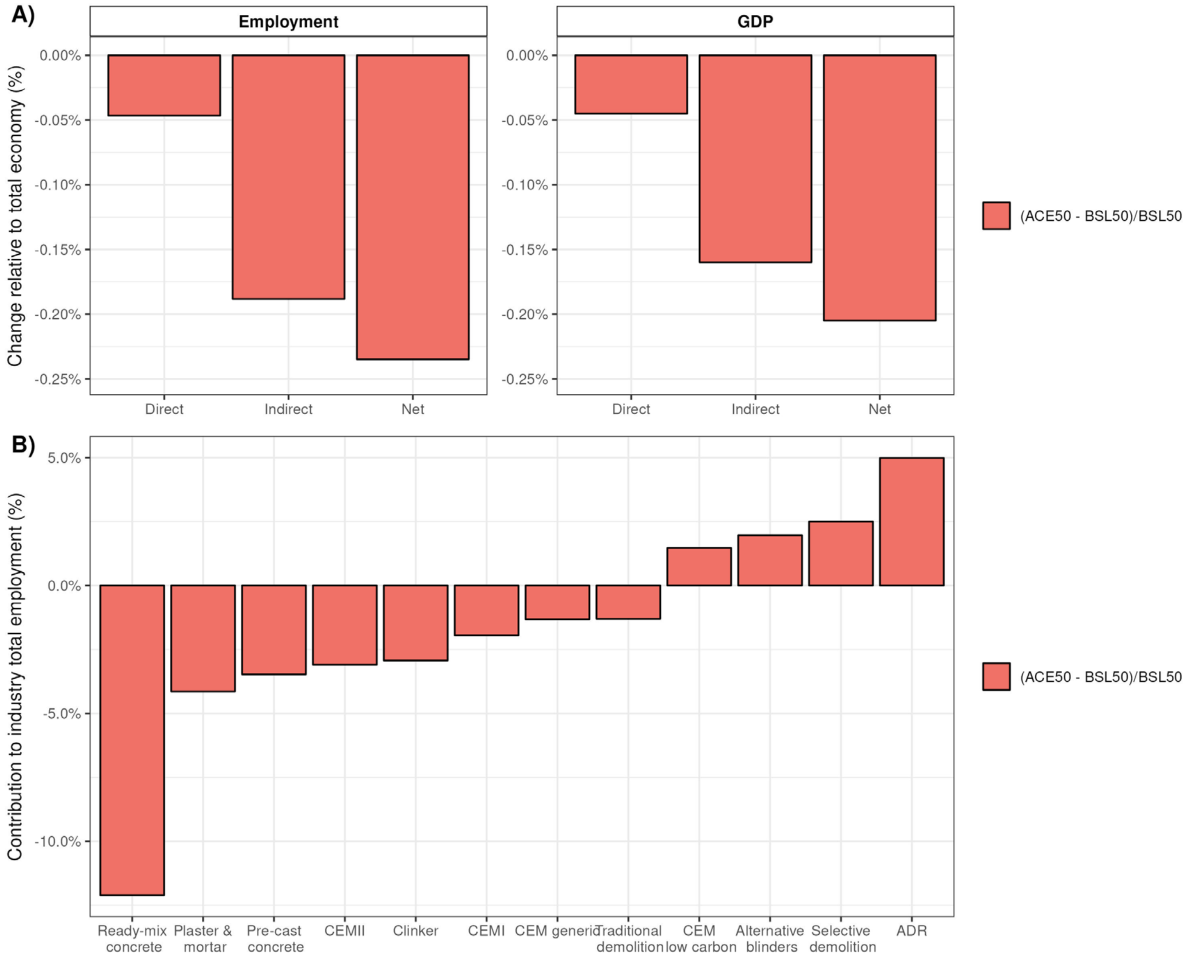
Source: JRC elaboration

5.2.3 Employment and value added

Figure 23 presents the reallocation of employment and GDP between the Circularity and Baseline scenarios (ACE50-BSL50). The results in Panel A indicate that there are significant shifts of the magnitude of 30% within the cement and concrete industry, with respect to the BSL50. Indirect effects upstream (reduced quarrying, accounting a quarter of the reduction) and downstream (reduced construction, making up 2/5 of the reduction) on the other hand, are mainly negative. It is worth noting that the EEIO modelling is a linear model that does not account for changes in labour productivity and instead assumes an equal number of jobs per unit of output for all cement industries. Moreover, the re-allocation of productive factors to, for example, service sectors is also not included. However, it does capture changes in the economy, as it adjusts to a new supply and demand balance, which has implications for supply chain configurations. In this context, a decrease of approximately 0.23% in total employment and 0.2% in EU GDP is observed.

Panel B provides insight into the offsetting effect between different cement activities. Some activities, such as the different types of concrete and mortar, or cement and clinker support fewer jobs than projected by BSL50, resulting in decreases of 4-12% and 1.3-3.1%, respectively. In contrast, others create more jobs, with the most notable cases being ADR recycling and selective demolition, as well as alternative binders which see increases of 5%, 2.5% and 2% in jobs, respectively.

Figure 23. Changes in EU employment and gross domestic product (GDP) between the Circularity and Baseline scenario and changes in employment for specific cement industries in comparison to total industry in 2050



Note: Changes in % of EU employment and gross domestic product (GDP) between the Circularity and Baseline scenarios (ACE50-BSL50) for direct jobs and GDP contribution in the EU cement industry, indirect jobs/GDP in other industries in the supply chain, and net changes in comparison to the total economy (panel A). Changes in % of employment in the Circularity and Baseline scenarios (ACE50-BSL50) for specific cement industries in comparison to total industry in 2050 (panel B).

Source: JRC elaboration

6 Dynamic macroeconomic modelling with FIDELO

Comprehensive modelling approaches capable of capturing the dynamic complexity are essential for evaluating transition pathways. To add to the results of the static methods in the previous chapters, dynamic economic modelling provides a complementary view of economic rebound effects. The Fully Inter-country Dynamic Econometric Long-term Input-Output model (FIDELIO) developed by the JRC is applied to add to the insights of the other methods.

6.1 Methodology

Dynamic economic modelling captures the relationships between different agents in an economy. While IOA covers the relationship of the final demand to industries, dynamic modelling approaches such as FIDELIO extend the representation of economic relationships by covering flows from businesses to households in form of wages or by linking government spending to taxation of firms. Most prospective macroeconomic studies of the CE are centered on dynamic approaches such as macroeconometric analysis (ME), computable general equilibrium (CGE) models and integrated assessment models (IAM) (Aguilar-Hernandez et al., 2018). While CGE models build on theoretical assumptions in their micro foundation, ME models are primarily based on empirical data relying on historical time-series to estimate parameters and relationships between economic variables over time. Compared to ME, the theoretical assumptions of CGE on cost-optimizing behaviour are less time sensitive and macroeconomtric models are therefore often applied primarily for the short and mid-term. Dynamic models are well suited to highlight rebound effects of the CE, including insufficient substitutability between primary and secondary products and price effects related to lower quality secondary goods (Zink & Geyer, 2017). The quantification of rebound effects is often omitted in CE impact assessments (Donati et al., 2020; Wiebe et al., 2019) but can be assessed using dynamic models such as FIDELIO.

6.2 FIDELIO

FIDELIO is a global demand-driven dynamic macroeconomic model that combines elements of input-output analysis, macro econometric analysis and computable general equilibrium modelling. It is based on Eurostat's official FIGARO supply-use tables (SUT) covering 64 industries and products in 46 countries and regions, with 2015 as the base year. FIDELIO 4 is structured in modules to increase transparency and traceability of macroeconomic effects. Thereby, the model is extended step by step with blocks of equations. Starting with a static supply-use table (SUT) model using a Leontief approach, the second module adds equations for investment dynamics. The third module adds consumption dynamics, and the full model includes price dynamics. The use of the full model is the most realistic due to its comprehensive representation of the economy and economic interactions. A brief description of the four modules is found in **Annex 13**, while a more detailed description of FIDELIO 4, including all equations, will be available in the forthcoming model documentation (Rocchi et al., 2025)

6.2.1 Modelling approach

The modelling approach is divided into two parts. First, the processing of shocks derived from the bottom-up LCA model for FIDELIO. Second, the implementation of the BSL50 and ACE50 scenarios in FIDELIO. Using all FIDELIO modules was beyond the scope of this study, and it is therefore limited to the full FIDELIO model for the most comprehensive representation of economic interactions.

6.2.1.1 Processing shocks of the bottom-up model

As a starting point, the EU-wide levers from the bottom-up model are assigned to their respective matrix, product, industry or end-use category in the FIGARO SUT. Due to the missing representation of stocks in the SUT data, only flows from the bottom-up model are implemented. An interface between the MFA/LCA bottom-up model and **FIDELIO** was developed, to effectively bridge the different spatial, sectoral and temporal granularity of the methods.

- **Spatial**: The granularity of the MFA/LCA bottom-up model perspective is aggregated spatially at the EU level, while FIDELIO uses country-specific data. To implement the CE levers in FIDELIO from the bottom-up models, their outputs must be distributed to the national level. This was done by aggregating the EU wide market in the FIGARO SUT, and calculating national market shares of the 27 member states. The shares are applied as a weighting factor to distribute the EU-wide shock to the national level.
- **Sectoral**: While the MFA/LCA bottom-up model includes a detailed representation of stocks and flows in different production stages as well as recycling for plastics, the sectoral granularity of FIDELIO is less comprehensive. To map the physical flows in the MFA to the monetary flows of FIDELIO, the data of the MFA is aggregated to a level compatible with the broader sectoral flows of FIDELIO. Where the flows in the MFA / LCA bottom-up model (e.g. cement and concrete) still represent only a fraction of a broader sector in FIDELIO (e.g. non-metallic mineral products), a market penetration rate was calculated using the highly disaggregated IO table FIGAROe3 and ProdCom. The market penetration rate was then applied as a second weighting factor to bridge between the different sectoral granularities. This approach is adapted from Donati et al. (2020).
- **Temporal:** FIDELIO uses yearly data while data from the bottom-up MFA/LCA model is available for the status quo year 2022 and the target year 2050. For implementing bottom-up scenarios from the MFA/LCA model interpolation is necessary. In this study, an S-shaped logistic growth function is used to interpolate values from the bottom-up model. This function is common for modelling diffusion processes and begins with exponential growth, that slows until a saturation point is reached (Sterman, 2000). For this study, it describes the implementation level of the applied levers between 0% to 100%, accounting for full implementation between 2030 and 2050.

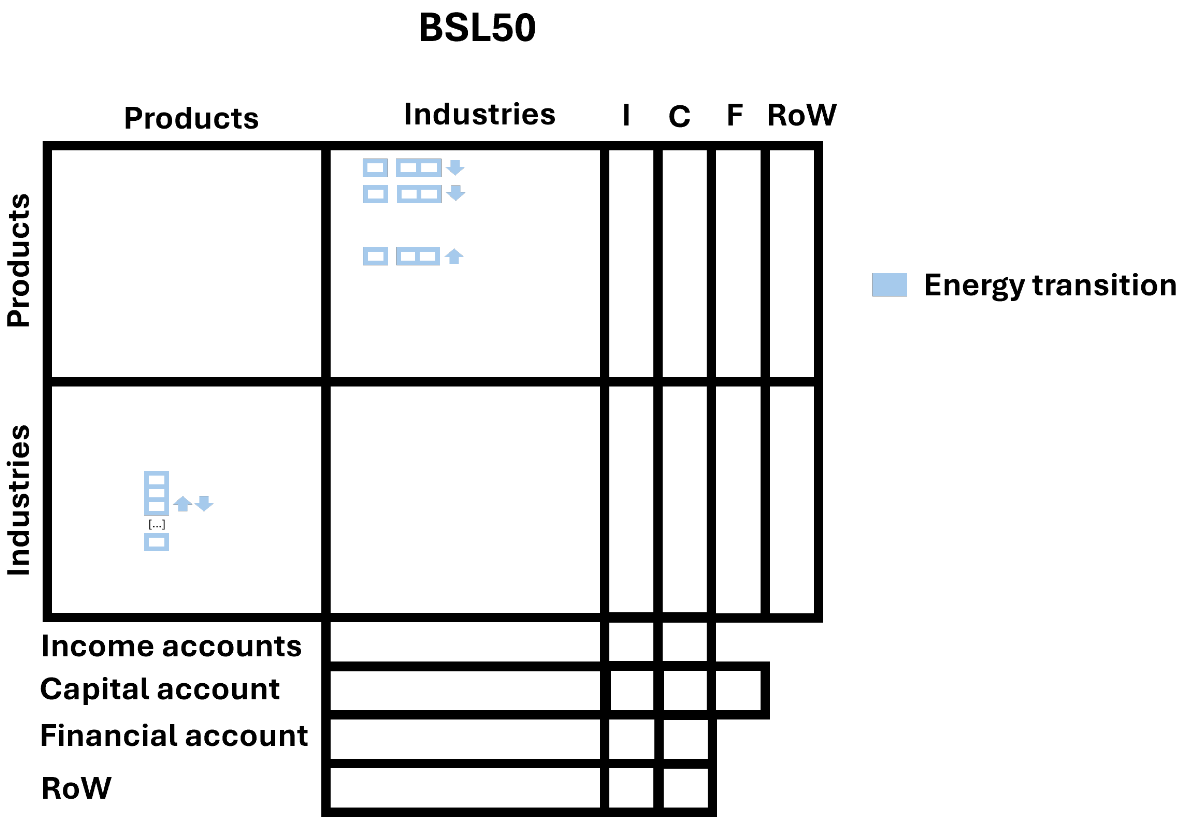
By combing both weighing factors and interpolating for annual time steps, the changes are distributed to the national level. These steps are repeated for all relevant flows of the bottom-up model. The relative change in physical units of the bottom-up model is applied as a likewise relative change in the monetary units of FIDELIO. This simplifies the process and avoids price uncertainties. However, it is possible to use this approach by monetising the physical quantities first and then adding an additional step to adjust for differences in national price levels.

6.2.1.2 BSL50

For the baseline scenario BSL50, three main trends are included based on the NDC-LTS scenario from the Global Energy and Climate Outlook 2023: Economic growth, energy transition and electrification. Thereby, the national GDP growth rates were adjusted to follow the GECO 2023.

Energy is represented in FIDELIO by the product ‘Electricity, gas, steam and air conditioning’ (CPA_D35), co-produced by 14 disaggregated industries of D35, and ‘Coke and refined petroleum products' (CPA_C19) mainly produced by industry 'Manufacture of coke and refined petroleum products' (C19). Using those two industries, decarbonisation is employed in the BSL50 scenario by including two main trends: Phase-out of fossil fuels in the production of electricity and electrification as illustrated in the GECO 2023.

Figure 24. Implementation of the energy transition in the BSL50 scenario



Note: C: Capital account; F: Financial account; I: Income account; RoW: Rest of the World. Blue boxes in the National Accounting Matrix used by FIDELIO indicate changes in monetary flows, colour-coded for each scenario and assigned arrows to indicate increases or decreases.

Source: JRC elaboration

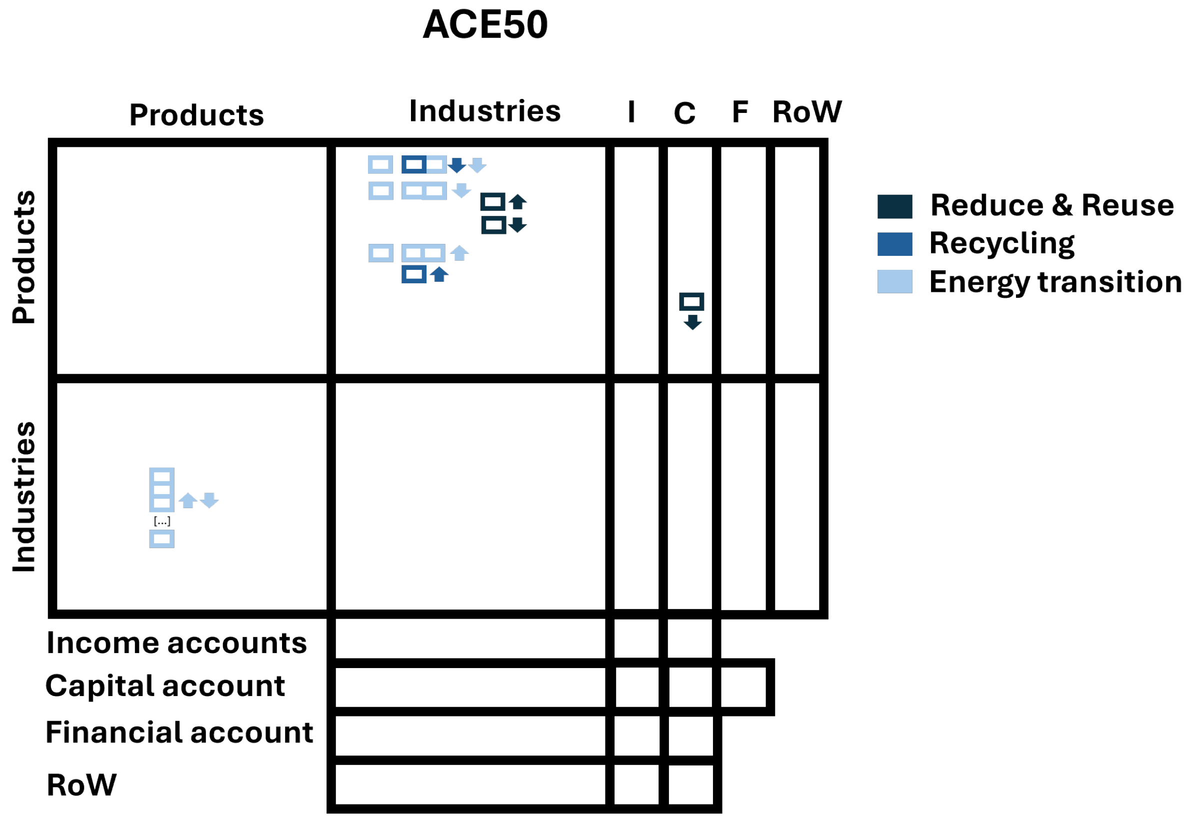
The transition away from fossil fuel-based electricity is reflected by lowering their production share in the supply matrix following the energy shares of the GECO NDC-LTS scenario. Electricity is co-produced by 12 main industries in FIDELIO representing fossil and renewable energy carriers. Additionally, FIDELIO covers the transmissions and distribution of electricity in one industry and Gas, steam and heat in another industry. The electrification of the energy sector is included by increasing the shares of electricity production and transmission, while lowering that of Gas, steam and heat. The ratio between electricity production and transmission were thereby kept static. In addition, the energy consumption of the energy intensive industries steel, aluminium, cement and concrete and plastics were adjusted using data from the GECO 2023. This was done by adjusting the intermediate use of the industries Basic metals (C24), Other non-metallic mineral products (C23) and Chemicals and chemical products (C20) based on the respective market penetration rates of steel, aluminium, cement and plastics from the disaggregated IO table FIGAROe3. Following the data from the GECO 2023, this included a phasing-out of fossil fuels such as Coke and refined petroleum products (CPA C19) and Mining and Quarrying (CPA B), while increasing the consumption of Electricity, gas, steam and air conditioning (CPA D35). The energy expenditure in the intermediate input is thereby kept constant, and energy efficiency or an increase in energy expenditure, for example for green hydrogen, is not explicitly considered and can be investigated more closely in the future.

Overall, the baseline covers electrification using an energy mix primarily from renewable energies for import industries and final uses. The GECO NDC-LTS scenario relies on increases in energy efficiency for agriculture, industries and services plus technologies such as carbon capture and storage (CCS) to reach European net zero goals in 2050. A full replication of the GECO analysis using FIDELIO was considered as out of scope for this study and therefore net zero is not achieved in the EU in the BSL50 in FIDELIO.

6.2.1.3 ACE50

The ACE50 scenario described in 2.2.4 covers a reduction due to material efficiency, material substitution, product lifetime extension, and an increase in recycling. This is implemented by changing the intermediate use of two industries. In Manufacture of other non-metallic mineral products (C23), the consumption of Mining and quarrying (CPA B) products is reduced due to increased recycling. The decrease in CPA B is counterbalanced by a proportional increase in waste management in Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery services; remediation services and other waste management services (CPA E37T39), assuming a constant price. Given the large uncertainties in forecasting future resource prices, this is considered a feasible approach (Wiebe et al., 2019). Moreover, the intermediate use of the cement and concrete in CPA C23 is reduced for Construction (F) for following the introduction of reduce and reuse levers. Moreover, one of the reduce levers, the substitution of concrete with wood is modelled by correspondingly increasing the share of 'Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials' (CPA 16) in Construction (F). Finally, due to extended product lifetime, less demolition services are required. This is modelled by reducing the final demand for Constructions and construction works (CPA F) in the final demand. **Figure 25** illustrates the modelling approach. It needs to be underlined that the levers related to the substitution of clinker raw materials with recycled cement fines or fly ash from co-processing, as well as the substitution of clinker and cement itself are not modelled, due to the high aggregation of the FIGARO 64 tables. Therefore, the effects of these levers are not taken into account, as they would all be applied within C23, while keeping mass flows constant. The impact of their omission is expected to have negligible impacts on GDP, trade and employment, given the substitutions are happening within the same sector. However, as these levers have a potentially high impact on GHG emission savings, the climate change results will only be analysed with respect to potential unexpected rebound effects in the dynamic model. Meanwhile, the magnitude is considered more reliable from the LCA and EE-MRIO results.

Figure 25. Implementation of CE shocks in the ACE50 scenario



Note: C: Capital account; F: Financial account; I: Income account; RoW: Rest of the World. Blue boxes in the National Accounting Matrix used by FIDELIO indicate changes in monetary flows, colour-coded for each scenario and assigned arrows to indicate increases or decreases

Source: JRC elaboration

6.3 Results

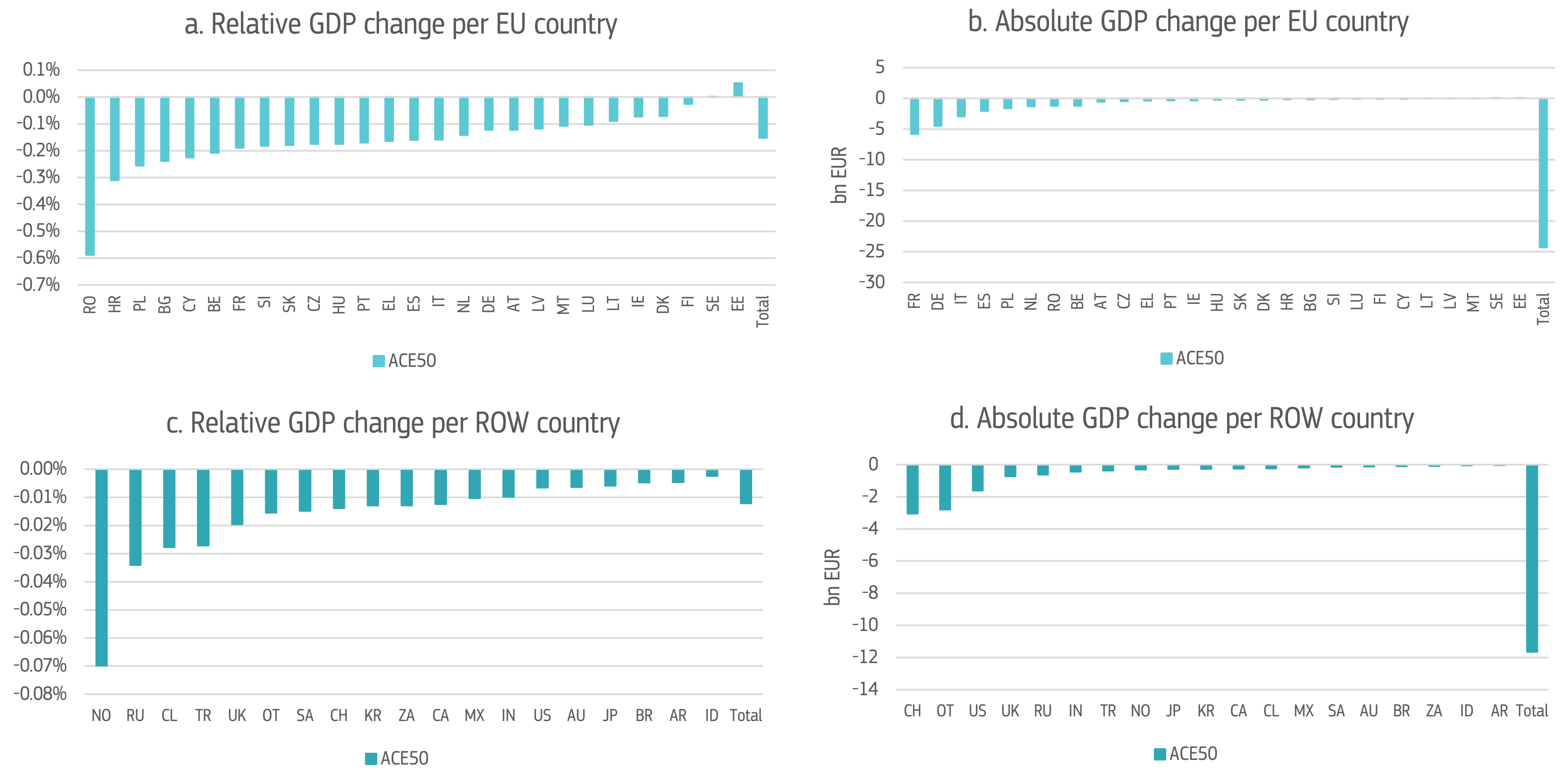
The following subsections will present the results for GDP, value added per industry, trade, and employment using the dynamic macro-economic model FIDELIO. The results are presented relative to the BSL50 scenario, which is taken as benchmark. Therefore, the difference between BSL50 and the ACE50 scenario is to be interpreted as the additional effect incurred by the implementation of the CE levers. It is thus possible that the ACE50 values are below those of BSL50, but still at a higher level than STQ20. Moreover, it needs to be reiterated that the CE levers related to SCMs and cement substitution were not modelled, due to the level of aggregation of the FIGARO tables that are used for FIDELIO.

The results include both the total absolute decrease (e.g. EUR billion or 1000 jobs) and relative decrease (%) compared to the baseline. The two offer complementary but different information: while the absolute change is strongly correlated to the size of a region or industry in the BSL50 scenario, the percentage should be interpreted as targeted impact due to the CE levers and, hence helps identify the most affected regions or sectors, regardless of their size.

6.3.1 Gross Domestic Product and Value Added

The ACE50 scenario shows a EUR 24 billion GDP decrease compared to the BSL50 scenario, implying a 0.15% decrease, as depicted in **Figure 26** a) and b). The largest decreases are in France, Germany, Italy and Spain, ranging from EUR 2 to 5.8 billion with respective relative decreases between 0.12% and 0.19%. In contrast, the highest relative decrease in the EU is in Eastern Europe, in Romania, Hungary, Poland and Bulgaria, ranging from 0.24% to 0.59%. **Figure 26** d) presents the absolute change in the RoW at EUR 12 billion, with China and the US showing the largest declines, whereas the biggest relative declines (between 0.027% and 0.07%) shown in **Figure 26** c) are in Norway, Russia, Chile and Turkey. Overall, the declines in RoW are negligibly small and mainly related to 'Mining and quarrying' (B) and 'Crop and animal production, hunting and related service activities' (A01). On a global scale, the EU makes up 14.18% of the GDP in the BSL50 scenario, which reduces to 14.17% (i.e. 112 trillion EUR) the ACE50 scenario, indicating a minimal change.

Figure 26. Absolute and relative change in GDP in EU and rest of the world (RoW)


a. Relative GDP change per EU country

b. Absolute GDP change per EU country

c. Relative GDP change per ROW country

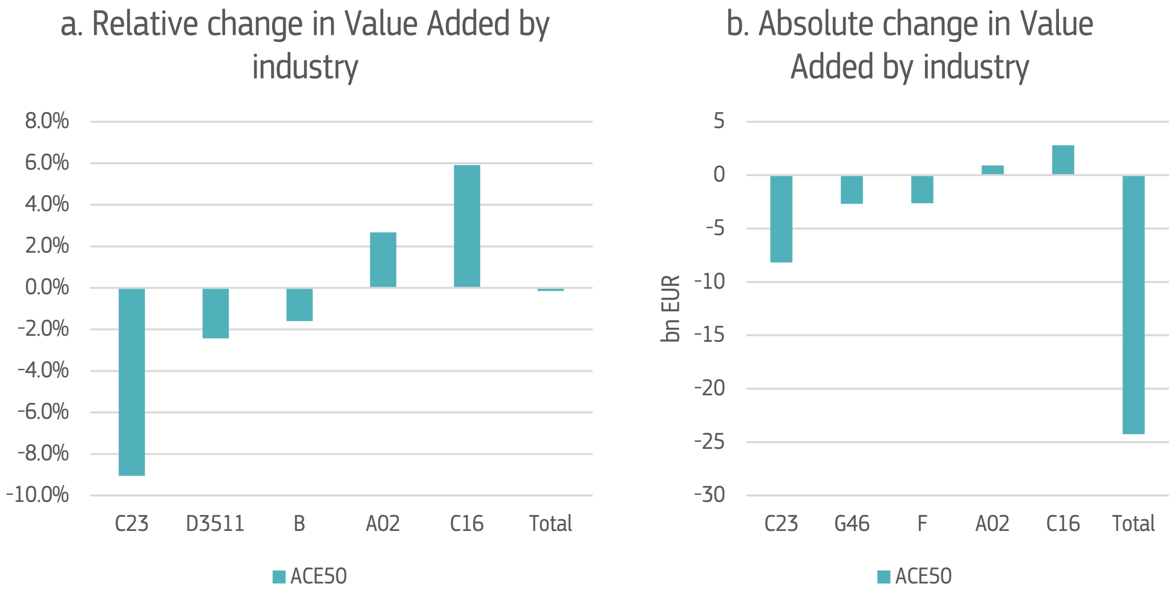
d. Absolute GDP change per ROW country

Note: Panel a) relative change in GDP per EU country (in %) for ACE50 scenario; panel b) absolute change in GDP per EU country (in billion EUR) for ACE50 scenario; panel c) relative change in GDP per non-EU country (in %) for ACE50 scenario; panel d) absolute change in GDP per non-EU country (in bn EUR) for ACE50 scenario

Source: JRC elaboration

With respect to changes in GVA in EU industries, **Figure 27** a) shows that the main affected industries are ‘Manufacture of cement, lime and plaster’ (C23) as well as ‘Production of electricity’ (D3511) and ‘Mining and quarrying’ (B) with decreases of 9.1%, 3.1% and 1.6% respectively. In contrast, the ‘Forestry and logging’ (A02) and ‘Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials’ (C16) are increasing at 2.6% and 5.9%, given the replacement of concrete with wood. The corresponding absolute GVA changes from **Figure 27** b) are decreases of EUR 8.1 billion for C23, EUR 2.7 billion for ‘Wholesale trade, except of motor vehicles and motorcycles’ (G46), EUR 2.6 billion for Construction (F) and increases of EUR 0.91 billion for ‘Forestry and logging’ (A02), related to the EUR 2.8 billion increases in the wood manufacturing sector.

Figure 27. Absolute and relative change in value added by industry



Note: Panel a) relative change in Value Added for the EU at industry level (in %) for ACE50 scenario; panel b) absolute change in Value Added for the EU at industry level (in billion EUR) for ACE50 scenario

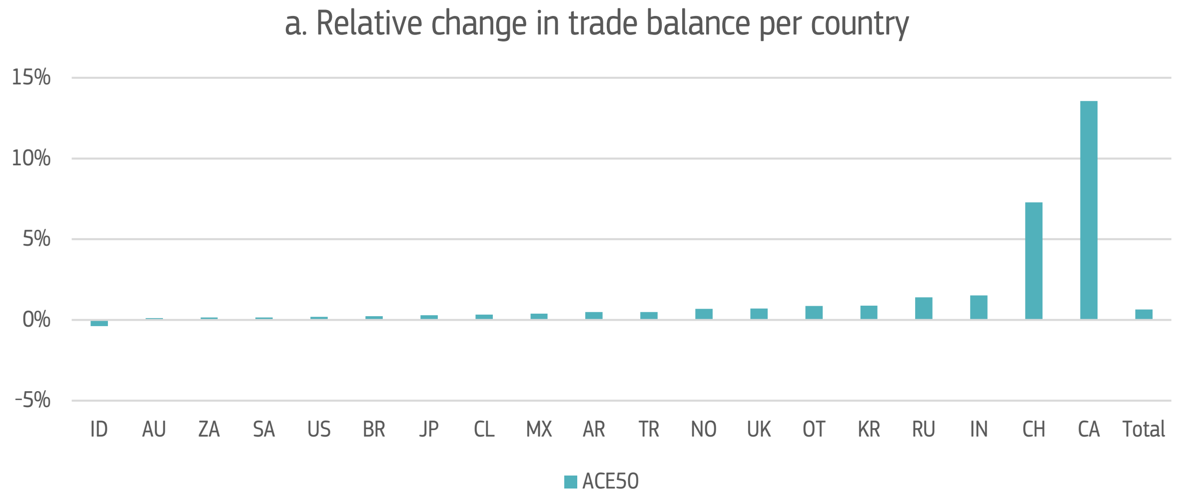
Source: JRC elaboration

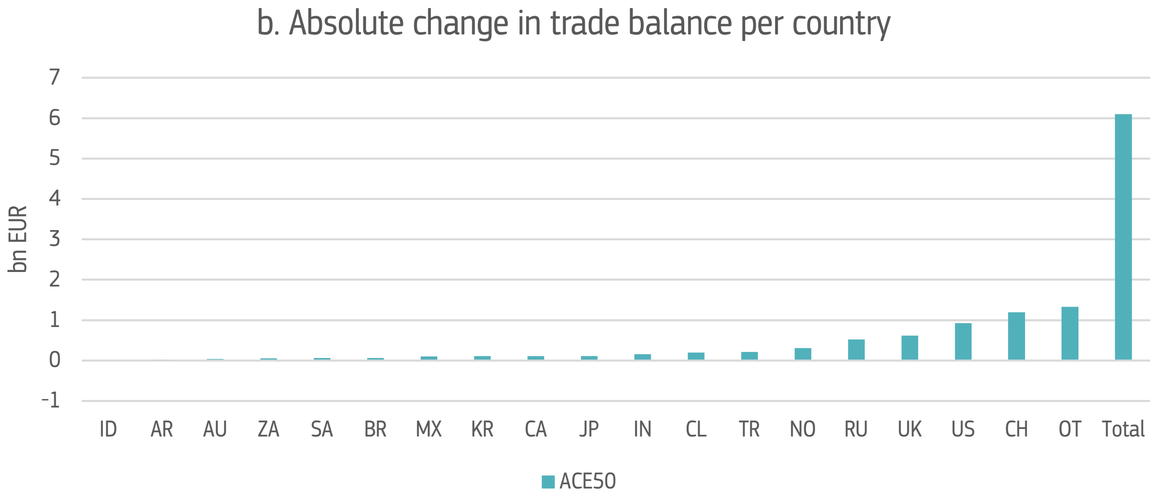
6.3.2 Trade

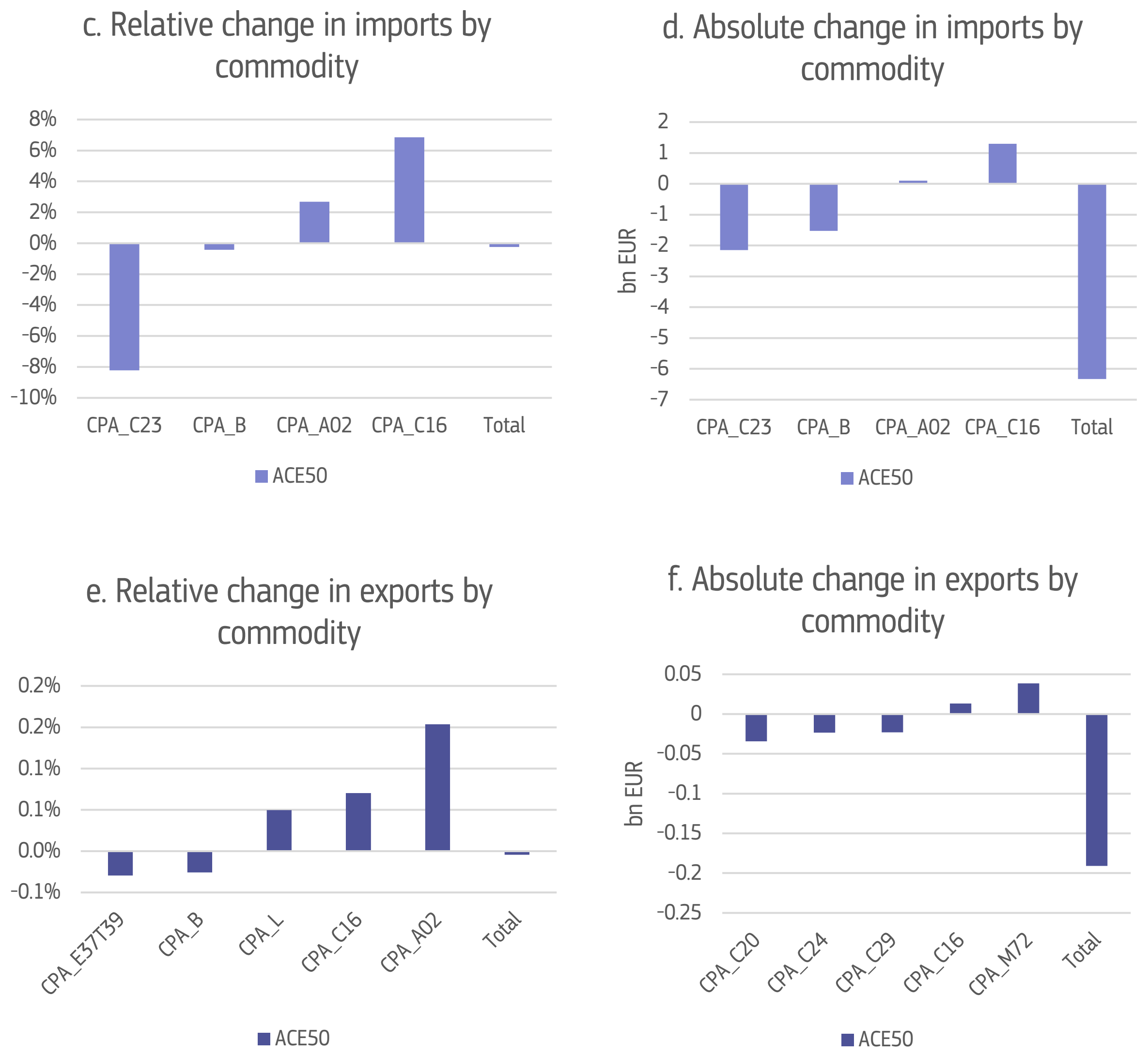
With the implementation of CE levers, the trade balance of the EU versus third countries is expected to increase by 6.1 billion EUR, representing a 0.64% increase of the existing trade surplus, as visible in **Figure 28** a) and b). The increase mainly stems from import decreases from China, US, UK and Russia, ranging between 0.52 to 1.2 billion EUR. In relative terms, depicted in **Figure 28** a), Canada (14%), and China (7.3%) show the biggest trade balance decreases.

Zooming into the imports, the magnitude of changes is 6.3 billion EUR, implying a 0.25% decrease in trade dependency. The absolute and relative decreases are the highest for products related to cement (CPA_23) at EUR 2.1 billion (-8.2%) and ‘Mining and quarrying’ (CPA_B) at EUR 2.5 billion (-0.4%), connected to quarrying (see **Figure 28** c) and d)). In contrast, there is a slight increase in imports of ‘Products of forestry, logging and related services’ (CPA_A02) and ‘Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials’ (CPA_C16) products, at EUR 0.097 billion (+2.7%) and EUR 1.3 billion (+6.9%) respectively. This is in line with the observations from the changes in GVA. Changes in exports are minimal in comparison, valued at a EUR 0.19 billion, representing a mere 0.0044% decrease. The main products affected by the decrease depicted in **Figure 28** d) are related to the plastics and metal sector (CPA_C20, CPA_C24), ranging between EUR 0.023 and 0.034 billion, while there are increases in exports of ‘Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials’ (CPA_16) at EUR 0.013 billion (0.07%) and ‘Scientific research and development services’ (CPA_M72) at EUR 0.038 billion.

Figure 28. Changes in trade balance by non-EU trade partner, and imports and exports by commodity


a. Relative change in trade balance per country


b. Absolute change in trade balance per country



Note: Panel a) relative change in trade balance per non-EU country (in %) for ACE50 scenario; panel b) absolute change in trade balance per non-EU country (in billion EUR) for ACE50 scenario; panel c) relative change in EU imports by commodity (in %) for ACE50 scenario; panel d) absolute change in EU imports by commodity (in billion EUR) for ACE50 scenario; e) relative change in EU exports by commodity (in %) for ACE50 scenario; f) absolute change in EU exports by commodity (in billion EUR) for ACE50 scenario

Source: JRC elaboration

6.3.3 Employment

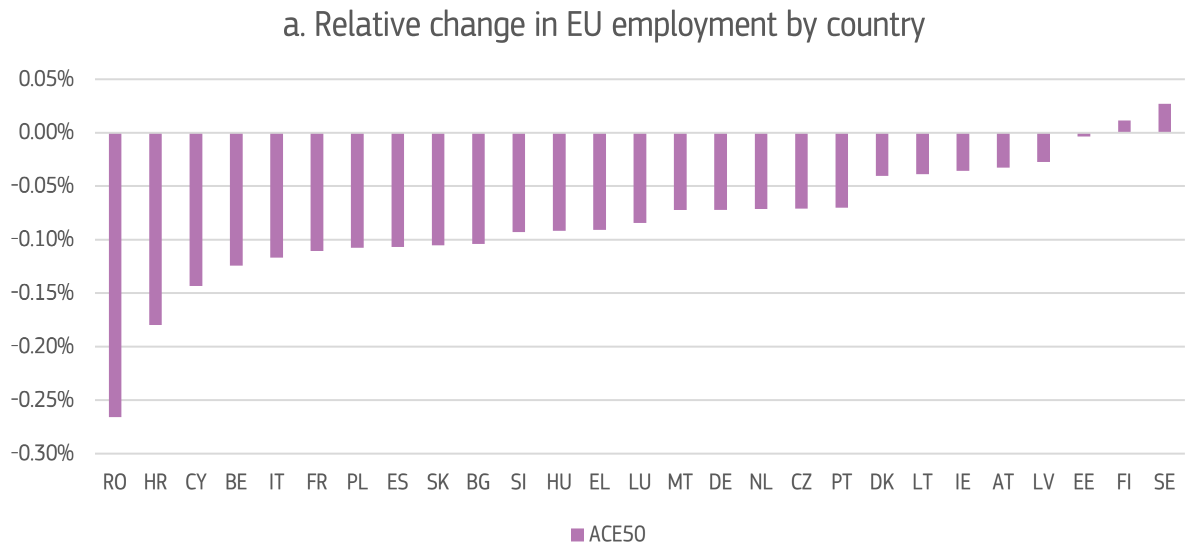
In the BSL50 scenario, the EU economy is predicted to offer about 177 million jobs. This number is reducing by 165 thousand jobs for the ACE50 scenario, as depicted in **Figure 29** b), implying a 0.093% reduction throughout the EU. The largest absolute reductions (see **Figure 29** b)) in employment are in Germany and France, followed by Italy and Spain, ranging between 19 and 30 thousand jobs. In relative terms, **Figure 29** a) shows that the largest declines are in Romania, Hungary, Cyprus (between 0.14 and 0.18% decrease), whereas Finland and Sweden exhibit slight increases (between 0.01 and 0.03%), related to forestry.

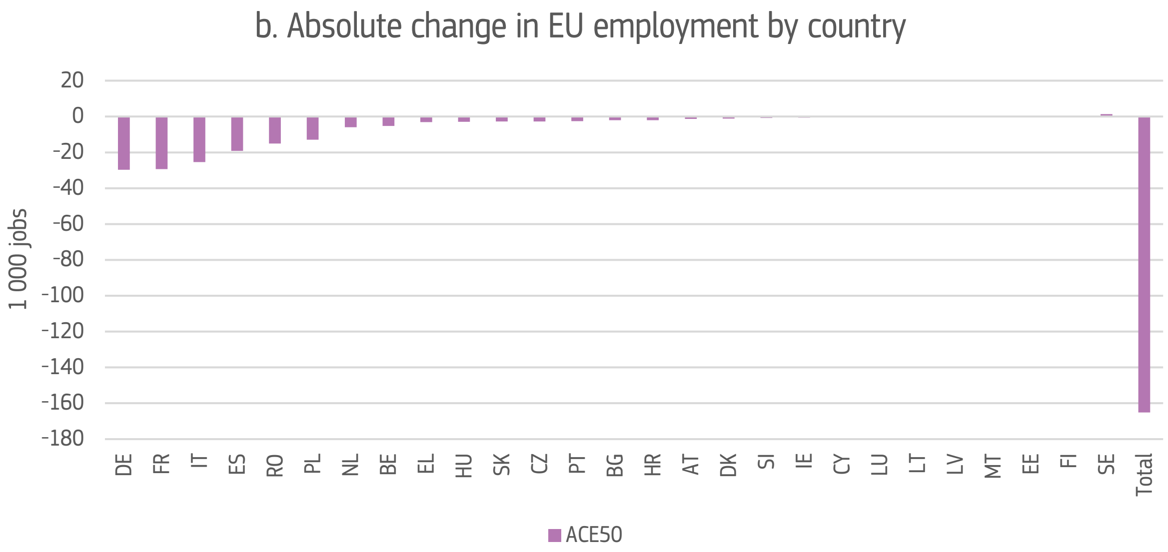
When taking an industry perspective, shown in **Figure 29** c) and d), the pattern follows the one of GVA, with ‘Manufacture of cement, lime and plaster’ (C23) yielding a reduction in employment by

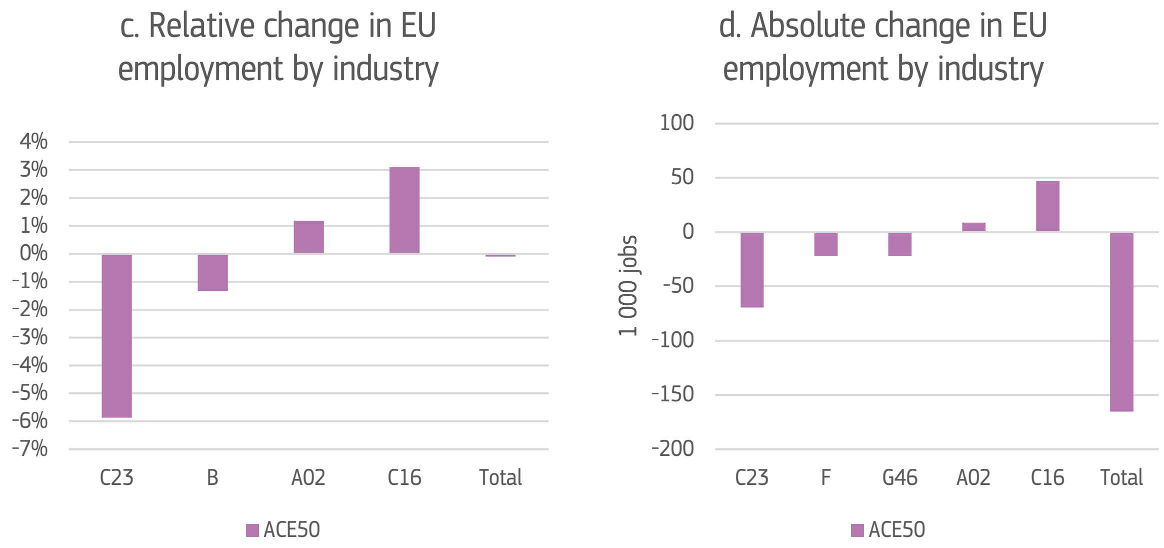
69 thousand jobs (corresponding to -5.9%). It is followed by ‘Construction’ (F) and ‘Wholesale trade, except of motor vehicles and motorcycles’ (G46) with respective reductions of 22.3 thousand and 22 thousand jobs. Due to the increased use of wood, Employment increases by 8.8 thousand jobs in ‘Forestry and logging’ (A02) and by 47 in ‘Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials’ (C16), which corresponds to relative increases of 1,2% and 3.1% respectively. A closer look at **Figure 29** c) additionally shows that notable relative decreases can also be observed in the ‘Production of electricity’ (D3511), losing 2.2% and the ‘Mining and quarrying’ (B), slightly shrinking at 1.3%.

With regards to the rest of the world, the largest decreases in absolute terms are in China and India (between 8-17 thousand jobs), while the main industries affected abroad are ‘Mining and quarrying’ (B), with a reduction of 144 thousand jobs and the ‘Crop and animal production, hunting and related service activities’ (A01), shrinking by 87 thousand jobs, followed by ‘Construction’ (F) decreasing by 51 thousand jobs with regards to the BSL50.

Figure 29. Change in absolute and relative employment per EU country and EU industry







Note: Panel a) relative change in employment by EU country (in %) for ACE50 scenario; panel b) absolute change in employment by EU country (in 1000 jobs) for ACE50 scenario; panel c) relative change in employment by EU industry (in %) for ACE50 scenario; panel d) absolute change in employment by EU industry (in 1000 jobs) for ACE50 scenario.

Source: JRC elaboration

6.4 Limitations

Decarbonisation in this study is focused on the energy sector and the four energy-intensive industries steel, aluminium, cement and plastics. The electrification of service sectors such as transport and residential energy use, as well as energy efficiency and the market diffusion of carbon capture technologies or green hydrogen were considered as out of scope. The analysis with FIDELIO in the BSL50 scenario therefore lacks the depth of the energy transition in the Global Energy and Climate Outlook 2023 and should be further investigated to examine the long-term contributions of the CE in more detail. An integrated approach combining FIDELIO with an energy system model at the appropriate spatial and sectoral level of detail, as recommended by (Elberry et al., 2024), and an MFA or LCA model to track stocks and flows of the evolution towards a CE would be a way forward, allowing to build on the specific strengths of the different types of modelling.

FIDELIO allows to use a modular approach. This study was limited to the use of the full model and therefore missed the traceability of macroeconomic spillovers and rebounds that is offered by using the different modules of FIDELIO to track intersectoral, investment, income and price effects. Using all modules would increase the depth of the analysis. A replication of the results using the other modules of FIDELIO can be considered to increase the traceability and transparency of the results.

The study is limited to the sectoral granularity of FIDELIO. Although the level of detail is comparatively high compared to other dynamic macroeconomic models used for CE analysis, there is a bias due to aggregation error. For example, the mining sector (NACE B) includes both energy extraction, such as coal, gas and oil, and non-energy extraction, such as stone and sand. Therefore, modelling a reduction of quarrying aggregates by reducing mining inputs of CPA B will also lead to a reduction in energy inputs. Another aggregation error is found in industry E37T39, which includes GHG-intensive processes such as waste incineration or processing of sewage sludge, in addition to the collection and processing of secondary materials. A further disaggregation of FIDELIO for non-energy mining and a differentiation of the waste streams for processing of secondary materials, incineration, landfilling or sewage services would help to better capture the changes due to the CE. This can be based on the highly disaggregated IO table FIGAROe3, following the example of the disaggregated energy sector used for this study. For the mining sectors, data quality checks can be carried out using the OECD's ICIO tables, which distinguish between energy and non-energy mining as well as mining support services. A CE sector specific disaggregated version of FIDELIO would allow future CE research projects to reduce the aggregation bias in FIDELIO. However, in dynamic economic modelling, an increased number of industries in models comes at the cost of reduced data reliability The data available for parameter validation is retrospective, spatially limited, and restricted to a unique setting, leading to limitations on the total number of industries used in dynamic macroeconomic models (Duchin & Levine, 2016). The trade-off between the benefits of higher sectoral granularity and lower data reliability should be considered when increasing the number of sectors in the model.

The dynamic modelling approach is consistent with the EEIOA, where shocks are implemented in the intermediate use matrix. However, this approach treats CE interventions as cost reductions. While the literature on CE rebound effects suggests that cost reductions through CE are likely and can lead to environmental rebound effects (Zink & Geyer, 2017), CE usually requires more services, which may partially counteract the cost reductions. This study used a combined approach of MFA, LCA and macroeconomic modelling. While this approach is rich in information on stocks and flows of cement and concrete, additional data inputs are required to take into account renovation and maintenance services, as well as research and development activities, that are important for longer product life, intensification of use and material efficiency. However, robust economic data for services were not available and were not specifically collected in this study. The consideration of this system boundary is important for the interpretation of economic indicators, such as GDP or employment, that do not include the increase in services required by the CE and should therefore be considered as a lower bound after technical optimisation of product design and processes to reduce material use. In addition to the costs of services, investment costs for alternative clinkers and binders, additional recycling infrastructure for cement fines and research facilities should be covered in more detail in the future. Future research projects can highlight these in more detail by adding data on life cycle costs, capital expenditure (CAPEX) and operating and maintenance expenditure (OPEX). This study highlights the potential to reduce industrial demand for cement and concrete rather than social innovations and impacts of behavioural change of consumers. Combining FIDELIO with a modelling approach that goes beyond the MFA inputs would allow scenarios of consumer behaviour change to be explored in more depth, broadening the scope of this study from technical optimisation to social innovation. This can be achieved, for example, through system dynamic or agent-based modelling approaches.

The trade pattern modelled in the BSL50 scenario of FIDELIO do not mirror the post Ukrainian-war situation. Therefore, in the changes in trade balances and patterns, the effect of CE levers on Russia is expected to be lower as a consequence to the implementation of existing European sanctions.

7 Discussion

This section is structured in two main parts. First, the results of the MFA, LCA, LCC, EE-MRIO and the dynamic macroeconomic modelling are synthesised and compared to the most relevant literature. The results from the different assessments are combined, and their origin indicated by footnotes. They are structured into effects on climate change and other environmental impact categories, effects on resource and trade dependency, as well as effects on socio-economic aspects, focusing on GDP and employment. It is important to reiterate that depending on the assessment method used, the results present a different level of detail and scope. Whereas the LCA and EE-MRIO are highly detailed on environmental impacts and energy inputs for the disaggregated sectors, they are less suitable for capturing trade, price and employment effects, due to their static nature. On the flipside, the dynamic macroeconomic modelling provides valuable information in these areas, but falls short in depicting certain CE levers, which is why its environmental effects are only referred to for identifying potential rebound effects, rather than absolute values. In a second part, policy measures intended to unlock the full potential of the CE levers are presented. They are proposed as part of a policy mix, covering the whole life cycle of the material and are either of economic, administrative or informative nature. The analysis lines out which existing or upcoming legislation already partially supports the CE lever implementation, and which levers would require further policy interventions addressing the reduce, reuse and recover clusters.

7.1 Effect on climate change

According to the LCA results, the decarbonisation measures presented by the BSL50 already indicate a 25% decrease from current values of about 137 Mt CO_2-eq. per year, which is similar to the 128 Mt CO_2-eq. identified by Cavalett et al. (2024). On top of that, the effect of adding CE levers, depicted in **Figure 30**, demonstrate a decrease in GHG emissions of the affected cement and concrete industry by 38-45%[5], corresponding to a 38-47 Mt CO_2-eq. decrease in the sector in the EU. The overall decrease, encompassing upstream and downstream emissions are up to 52 Mt CO_2-eq. globally, including rebound effects of 3 Mt CO_2-eq. in the Rest of the World (RoW), which are subtracted from the EU emission reduction of 55 Mt CO_2-eq[6]. The higher granularity of the LCA shows that most effective levers are situated in the *Reduce* cluster (leading to a 29 Mt CO_2-eq. reduction). This decrease is mainly linked to the substitution of clinker with other SCMs (both secondary and primary) (saving 15 Mt CO_2-eq., if applied individually) and is in line with the findings of other studies (Favier et al., 2018; Habert et al., 2020; Watari et al., 2022). Related savings in clinker production itself contribute about 83% of the total reduction[7]. While literature has advocated for more use of secondary materials such as granulated blast furnace slag or fly ash, our modelling has phased out these materials (resulting in a 7% reduction of GHG emissions) in the light of the energy transition (UN Environment et al., 2018; Zunino, 2023). Instead, other fillers such as limestone and in particular calcined clay are seen as key process innovations that promise low-hanging fruits for the cement industry. The reasons why they were not taken up until now have to do with the investment costs of retrofitting the cement production and industry inertia (Dewald & Achternbosch, 2016; Nilsson & Verschaeve, 2023).

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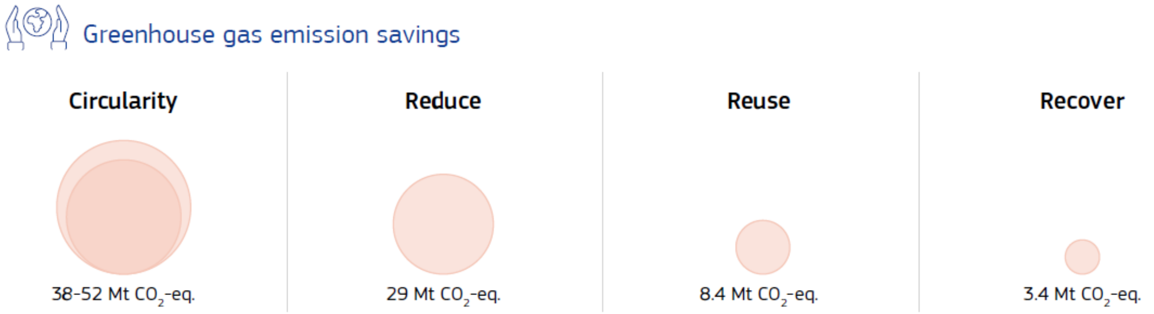
[5] The lower bound is calculated by the LCA and the upper bound by EEIOA.

[6] All numbers established by EEIOA.

[7] Established by EEIOA.

Figure 30. Savings of Mt CO_2-eq. emissions for the cement and concrete sector in the ambitious circular economy scenario and breakdown into the *Reduce*, *Reuse* and *Recover* clusters



Source: JRC elaboration

The second highly promising lever is the reduction of use of concrete in buildings (reducing 14 Mt CO_2-eq., if applied individually). The current overuse is largely due to, on the one hand, over-specification of use in building standards and, on the other, the practices of engineering bureaus working with standard quantities that go beyond safety standards (Habert et al., 2020). The reason that this overuse is still prevalent are the comparatively low material prices of concrete in the overall construction project. If the price were to more effectively include the environmental externalities, as is foreseen by the phase-out of the free ETS allowances, this tendency of overuse can be partially addressed.

A frequently proposed lever, namely increased use of wood instead of concrete has shown to have mainly negative effects on the environmental impacts. Even at a low substitution rate of 10%, it shows impacts that are 1.5-3[8] Mt CO_2-eq. above the baseline scenario values. This increase might have to do with a cautious modelling approach of the substitution rate (according to Andersen et al. (2022a)). Results of other studies have been much more optimistic, suggesting replacement rates of up to 50% for residential buildings (Le Den et al., 2020) and GHG savings of up to 50% for similar floor areas (m^2) (Duan et al., 2022). Given the higher emissions (embodied energy) due to the logging and decreases of energy emissions for industrial processes in the BSL50 vs the STQ20, this trade-off might in the future only be environmentally beneficial in specific regions (i.e. northern Europe). A similar trend is detected for Land Use, as forestry services needed for construction are increased by 17%[9]. This is related to the higher volume of wood necessary to replace structural concrete.

The *Reuse* cluster (resulting in an 8 Mt CO_2-eq. reduction), and especially the extension of lifetime provided considerable savings, though there, additional research is warranted regarding how this extension can be achieved (e.g. optimising existing building use or renovating buildings).

The *Recover* cluster overall yielded the lowest reduction potential (3 Mt CO_2-eq.), largely due to the smaller material flow of demolition, when compared to construction. As identified by the MFA, construction flows are currently 10 times larger than demolition flows and are projected to be five times larger by 2050. Yet, it is important to point out potential innovative technologies which can

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[8] The lower bound is calculated by EEIOA and the upper bound by LCA, with a more detailed modelling of the timber product.

[9] This is calculated by the EEIOA.

increase the capacity of recycling concrete waste into cement fines. These fines could replace calcareous marl in the raw material mix of the clinker, or cement itself, thus avoiding the most energy-intensive process of concrete production. Currently, recycling is focused on recycling concrete or mixed demolition waste back to aggregates, with negligible reduction potential from a CO_2 perspective and considerable additional costs (Caro et al., 2024). The LCA has shown that, compared to recycled aggregates, recycled cement fines save 20 times more GHG emissions. As apparent from this finding, using the circular material use rate (CMUR) as a reference indicator for policy has limited significance in the cement and concrete sector for both effects on climate change and value added. This is the case because, while the CMUR is expected to increase due to higher recycling of concrete aggregates, this does not lead to preferable environmental or economic outcomes in most cases. Instead, recycling to cement fines or raw materials is found to be more beneficial.

It is noteworthy, that the current policy discourse on CE in the built environment is mainly focusing on recycling, with the higher R-strategies largely absent. This is in stark contrast to the identified effectiveness of the levers, which is higher for the *Reduce* and *Reuse* cluster.

Concerning levers that would reduce demand of living space, this study has taken a conservative approach and not included them in the modelling. While there have been attempts to quantify the environmental effects reducing of living spaces or sharing of offices (Cohen, 2021; Vélez-Henao & Pauliuk, 2023), the societal implications of these more behavioural CE levers have not yet been assessed and underpin the reasoning for excluding these levers from the analysis. After all, the problem is not necessarily that society lives in houses that are too large, but that the living space is unequally distributed, and houses are used inefficiently. These topics require levers that reorganise the use and in certain cases access to living space, pointing towards political rather than technological solutions.

7.2 Effects on resource and trade dependency

The results discussed in this section are mainly from the EE-MRIO and the dynamic macroeconomic modelling. Given the higher degree of detail, energy flows are assessed with the static EE-MRIO, while the dynamic macroeconomic modelling allows for better understanding how the CE levers affect trade flows. With regards to energy dependency, an indication of the changes in purchases of selected energy carriers are presented in **Figure 31**. The results suggest that CE levers have a moderate impact on reducing market demand for electricity in the EU, with a decrease of 1.6% of the total region demand. Among fossil products, the greatest absolute and relative impact is observed in natural gas (needed for both heat and electricity production), for which the EU largely depends on imports (67% of total EU demand). The reductions predominantly stem from an overall reduction in the construction sector (accounting for about 44% to 66% of the change) as well as the cement, lime and plaster sector. Direct input of fossil energy carriers to the cement and concrete sector are reduced by up to 27% for natural gas, while savings also occur for coal (-20%) and crude oil (-22%). These savings are composed of reduced imports (almost half, in the case of natural gas) and reduced EU production of energy carriers. Finally, electricity use in the cement and concrete sector is reduced by 37%[10].

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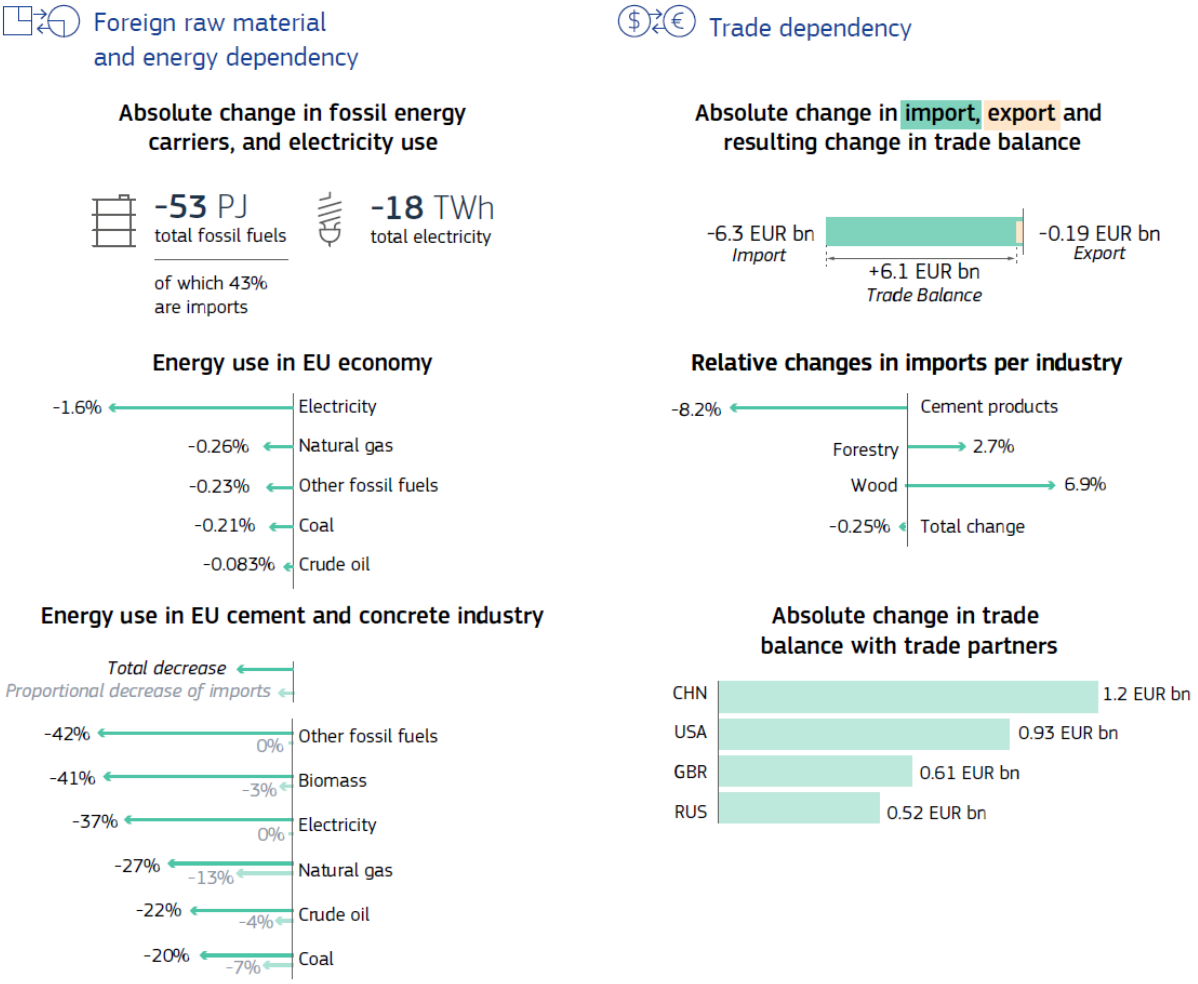
[10] All numbers are obtained by EEIOA, and include the energy carriers directly imported and embedded in the imports to the EU, both for satisfying EU demand and export.

Given the strong local character of this sector, current trade dependency is relatively small (a positive trade balance with 7% of domestic clinker demand covered by imports). In line with the reasoning that most CE levers are focusing on reduction, **Figure 31** shows overall imports decreasing by EUR 6.3 billion, with noteworthy changes in the cement sector, where imports are expected to reduce by EUR 2.2 billion, while imports from mining products also decrease by EUR 1.5 billion. In contrast, imports of forestry services and wood are projected to increase by EUR 0.097 and 1.3 billion, respectively. Meanwhile, exports decrease slightly at EUR 0.19 billion. This leads to a trade balance increase of EUR 6.1 billion, with the largest absolute changes (i.e. import decreases) occurring with the main trade partners China, USA, UK and Russia, while Canada exhibits the highest relative change[11].

Figure 31. Effects of CE levers applied in the cement and concrete sector on resource dependency and trade dependency



Note: Trade figures in real prices (base year 2015)

Source: JRC elaboration

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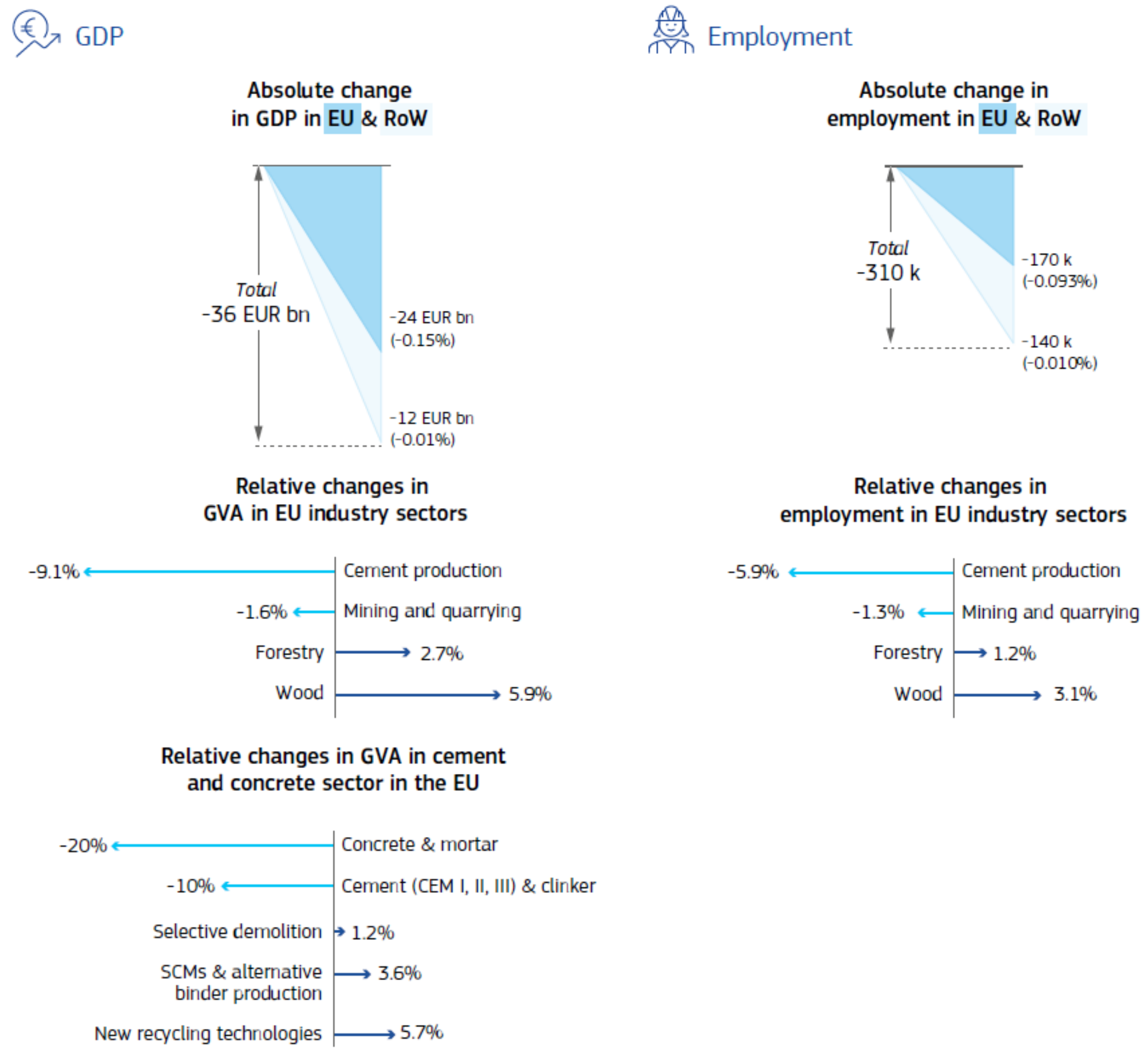
[11] All figures stem from the dynamic macroeconomic modelling, which has a higher aggregation of sectors and thus is less flexible in representing levers within the cement and concrete sector.

7.3 Effects on socio-economic factors

Figure 32. Effects of CE levers applied in the cement and concrete sector on GDP and employment



Note: GDP/GVA in real prices (base year 2015)

Source: JRC elaboration

At first glance, with the dynamic macroeconomic modelling, employment in the cement sector seems to decrease by 5.9% and CE levers have a limited impact in the rest of the EU economy (0.093%), with a projected decrease of about 170k jobs in the EU. However, a more detailed analysis of the sector exhibits a partial offsetting effect between different cement activities, which can only be captured by the more granular EEIOA[12]. It is worth recalling that the EE-MRIO is a linear model that does not account for changes in labour productivity and instead assumes an equal num-

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[12] It needs to be underlined that EEIOA is a linear model, and thus takes a simplified approach to reallocating jobs, by keeping the labour intensity in all affected sectors constant.

ber of jobs per unit of output for all cement industries. Moreover, the reallocation of productive factors to, for example, service sectors is also not included. Some activities, such as production of concrete and mortar, as well as clinker and cement (CEM I, II and III) production, will provide fewer jobs than projected in the baseline, corresponding to 20% and 10% of the change in the sector, respectively. In contrast, other sectors potentially create more jobs than in the baseline scenario, with the most notable cases being novel recycling technologies, alternative clinkers and cements, and selective demolition, which yield corresponding increases of about 5.7%, 3.6% and 1.2% in jobs. Besides the cement industry, quarrying activities are decreasing, leading to a 1.3% job decrease in the mining sector, while both the forestry sector and related wood sector increase by 1.2% and 3.1%, respectively (due to wood replacing concrete)[13]. A similar pattern is observed when analysing the life cycle costs (LCC), with a clear offsetting of jobs in quarrying aggregates with recycling processes. The EU economy-wide trends are similar for GVA (0.15% decrease, including price rebounds), as the cement and concrete sector (with a 9.1% decrease[14]) has significant spillover effects into the construction sector. LCC results show that production costs generally remain stable for CE levers that include substitution or decrease, but at lower rates than is the case for GHG emission savings. The only exception is the substitution of wood and the *Recover* cluster. The use of timber alone increases material production costs by 32%[15], an increase that has also been observed by other scholars (Duan et al., 2022). Moreover, the dynamic macroeconomic modelling indicates a 2.7% GVA increase in the EU forestry sector, and a 5.9% increase in EU wood products corresponding to EUR 0.92 and 2.8 billion, respectively. Concerning recycling, it was found that processing costs at the end-of-life will increase, due to more frequent recycling, but that this price hike is partially offset with the revenues of the secondary materials. The sales of secondary materials are expected to increase further, when novel recycling processes for recycling concrete into cement fines are at scale. Finally, it needs to be underlined that the decrease in GVA, established by the EE-MRIO, in the EU economy versus the baseline (-0.20%) is 22 times smaller than the decrease in GHG emissions (4.5%)[16], suggesting an increased decoupling of economic growth and GHG emissions incurred by CE levers. Moreover, both macroeconomic models project that the cement and concrete sectors will grow versus the status quo of today, but the growth in the ACE50 is slightly lower than projected in the BSL50.

These findings are subject to the significant limitation that the analysis has taken simplified assumptions on potential Gross Value Added or employment increases, taking a ceteris paribus assumption of the capital and labour shifts from the production to the service sector. Additional research or management services will be required to enable the implementation of innovative recycling technologies and maintenance of spaces, which are currently not accounted for. These factors are heavily dependent on human behaviour and the replacement rate of production vs. increase in services has only sparsely been addressed by scholars. These systemic shifts in financial flows merit in-depth research to better understand the potential and representation of circular business models in macroeconomic models.

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[13] These figures are from macroeconomic dynamic modelling. They show similar trends to the negative effects observed in the EEIOA, which are responsible for the largest share of employment decrease.

[14] As the FIDELIO model only allowed for a limited integration of recycling and novel cements, the offsetting effect might be larger.

[15] Established by LCC.

[16] Percentage taken from EEIOA, taking into account territorial GHG of the EU economy.

7.4 Key insights

In line with the findings above, a set of key CE levers have been identified. First, low carbon cement, including higher shares of SCMs should be promoted. This is a low hanging fruit, given the high technology readiness levels and abundance of SCMs, also paving the way for including recycled cement fines. Though some initial investment for retrofitting cement plants is necessary (Nilsson & Verschaeve, 2023), it enables GHG reduction at a lower price than carbon capture and storage, a finding shared by Watari et al. (2022). Secondly, the use of concrete can be reduced for non-structural purposes by reducing the overspecification in standards and using the material more economically. While future increases of the carbon prices may already provide an incentive to reduce the use of cement, updating the standards as soon as possible towards performance-based standards in the different member states would further increase the reduction potential. Moreover, the replacement of concrete with wood does not entail significant GHG savings in a future where energy is decarbonised and potentially increases production costs significantly, which is why it should be considered based on local resource availability and regenerative forestry practices. Reuse of structural and pre-cast concrete elements is to be facilitated by clarifying questions of insurance and safety considerations, which are frequently the most important barriers impeding reuse. Finally, recycling of concrete waste to recycled cement fines should be further developed and scaled up, given they bear a GHG savings potential 20[17] times higher than recycling to recycled aggregates only.

7.5 Potential policy instruments for the EU cement & concrete sector

The transition to a CE is a multi-level and multi-stakeholder long-term process that requires a well-aligned strategic direction and a carefully designed operational framework. The CE could contribute to mitigating resource and environmental constrains in the EU by addressing aspects of the climate and resource crisis, enhancing competitiveness in a global environment, strengthening the strategic autonomy of the EU, without diminishing the quality of life of EU citizens nor shifting environmental burdens elsewhere. This diversity of CE objectives causes considerable complexities for policymakers, since multiple policy objectives need to be fulfilled at the same time. Since there is no single policy instrument that would be equally suited for all problem areas, goals, actors, type of resources, life-cycle stages, etc., a systems perspective is required to prevent problem shifting, conflicting aims and incoherence among policy fields and implementation levels (Wilts & O'Brien, 2019).

It is widely recognised that supporting sustainability transitions, such as the CE transition, requires a consistent combination of strategies and accompanying instruments in so-called policy mixes (Sovacool et al., 2025). Within a policy mix, the synergies between various policy instruments address the complex challenges of CE more holistically, leveraging their strengths to target different aspects of a problem at different levels. A coordinated policy mix approach aims at mitigating potential conflicts or redundancy between policy instruments, ensuring coverage of various dimensions of the issue and enhancing the overall effectiveness of the applied policies (Howlett & Rayner, 2007; Rogge & Reichardt, 2016).

The EU cement and concrete sector consists of an extensive multi-actor value chain (see Figure 1), extending both within and outside the EU, and involving economic and societal actors at regional,

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[17] Established by LCA.

national and international levels. It becomes evident that a CE transition of the EU cement and concrete sector needs a systemic policy approach, designing a balanced policy mix targeting all CE clusters and actors involved.

To reduce the risk of burden shifting from one life-cycle stage to another, a wide systems perspective is required in the designing of a policy mix (Ekvall et al., 2016). This implies that the policy mix would target every stage of the life cycle of a process or product to avoid potential counteractive or unintended effects of the selected instruments upstream or downstream the supply chain, while in the meantime striving to achieve synergies between the various policy instruments to reinforce the anticipated outcome of the policy mix (Dalhammar, 2015). Therefore, in the context of CE, a carefully designed policy mix has the potential to result in a strengthened policy framework with a significant influence towards saving resources and increasing the mass and quality of circulated materials and products in the economy. The direct effects of the policy mix would be expected to have higher impact than what a mere combination of the individual policy instruments would be able to achieve, and would target proportionately all life cycle stages (Milios, 2018). Conceptually, a CE policy mix would include a set of complimentary policy instruments applied across the life cycle of materials/products.

7.5.1 Policy mixing principles

The three main reasons for adopting a policy mix approach can be summarised as multiple market failures (including transaction costs and information asymmetries), governance constraints, and behavioural factors (Bouma et al., 2019). Therefore, an effective design of a policy mix intervention requires a good understanding of the market, governance and behavioural failures that need to be tackled for the intended policy mix to have the desired effect. A policy mix approach should exhibit certain design characteristics to achieve a high level of efficacy in addressing the targeted problem(s). These characteristics are consistency, coherence, comprehensiveness, credibility, and congruence (Howlett & Rayner, 2007; Rogge & Reichardt, 2016).

Consistency refers to ‘how well the elements of the policy mix are aligned with each over, thereby contributing to the achievement of policy objectives’ (Rogge & Reichardt, 2016). Single instruments in a policy mix can be considered as consistent when they function synergistically to support a policy objective. This implies the elimination of contradictions between instruments and the existence of synergies within and between the elements of the policy mix. While consistency focuses on the contents of the mix, the term **coherence** focuses on the design policy process dimension (OECD, 2016). Consistency and coherence in a policy mix can be fostered by combining primary with supportive instruments. Primary instruments are mainly used to achieve a defined policy objective. Supportive instruments are used to minimise or mitigate unintended negative side effects of primary measures and, therefore, to increase their acceptability and feasibility (Rogge & Reichardt, 2016). **Credibility** refers to the extent to which a policy mix is considered reliable, which may be affected by several factors, such as the commitment from political actors, the consistency of the instrument mix, and the competence of the implementing authorities (Rogge & Reichardt, 2016). **Comprehensiveness** refers to the ‘…the degree to which the instrument mix addresses all market, system and institutional failures, including barriers and bottlenecks’ (Rogge & Reichardt, 2016). **Congruence** among instruments and (socio-economic) goals means the compatibility between the strategic objective of a policy goal and the design of the policy mix to achieve the intended outcomes (Howlett & Rayner, 2007).

In order to effectively respond to the specific context of a policy vision in a long-term perspective, the development of policy mixes needs to consider the following (Howlett & Rayner, 2007; Rogge & Reichardt, 2016):

- The full range of policy instruments (types of instruments, see section 7.2.3)
- The full cost of policies (including implementation, transaction and compliance costs)
- Avoiding negative interactions between single policies (i.e. instruments already in place and new ones) and emphasising mutual benefits and potential with existing policies
- The potentially negative side-effects of the instruments on the target groups, e.g. issues of competitiveness in industry or adverse effects on lower income households
- The political processes during the design and implementation of the mix

A comprehensive policy mix needs to go beyond just combining the individual policy instruments statically. In a policy mix, the long-term qualitative strategic objectives and short- to mid-term quantitative targets should be combined in a time-dynamic approach to effectively achieve the overall goals. A policy mix design also requires forward-looking strategic planning (foresight), by relating different policy instruments in a time sequence that enables the optimisation of synergistic effects while minimising the unintended negative side effects (Ekvall et al., 2016).

Moreover, the literature on policy mixes for sustainability transition processes emphasise that change does not materialise by fostering solely new solutions and innovations, but also by putting pressure on incumbents and the established socio-technical configurations, e.g. through phasing out existing measures that reinforce the status quo (Kivimaa & Kern, 2016; Sovacool et al., 2025).

7.5.2 Long-term policymaking considerations

Socio-economic transition processes take a long time and can have variable directions and outcomes, so a necessary strategic vision and appropriate policy instruments must be formulated in advance. The transition to a CE is expected to develop gradually over the following years and the impact assessment modelling in this study foresees anticipated outcomes by the year 2050. In this context, the notion of long-term policy design is coming to prominence. Fundamental elements to consider in long-term policy design include: 1) achieving extended coordination between the actors involved; 2) taking a holistic view on socio-economic and (parallel) political developments; 3) preventing unpredictable outcomes; 4) sustaining a vision for the long-term goals of the policy, without suppressing diversity; and 5) retaining adaptability towards the complex dynamics of change. In order to constructively deal with all these issues in long-term policy guidance, within a short-term context, most approaches to strategic planning pragmatically combine top-down and bottom-up considerations (Voß et al., 2009).

7.5.3 Typology of policy instruments

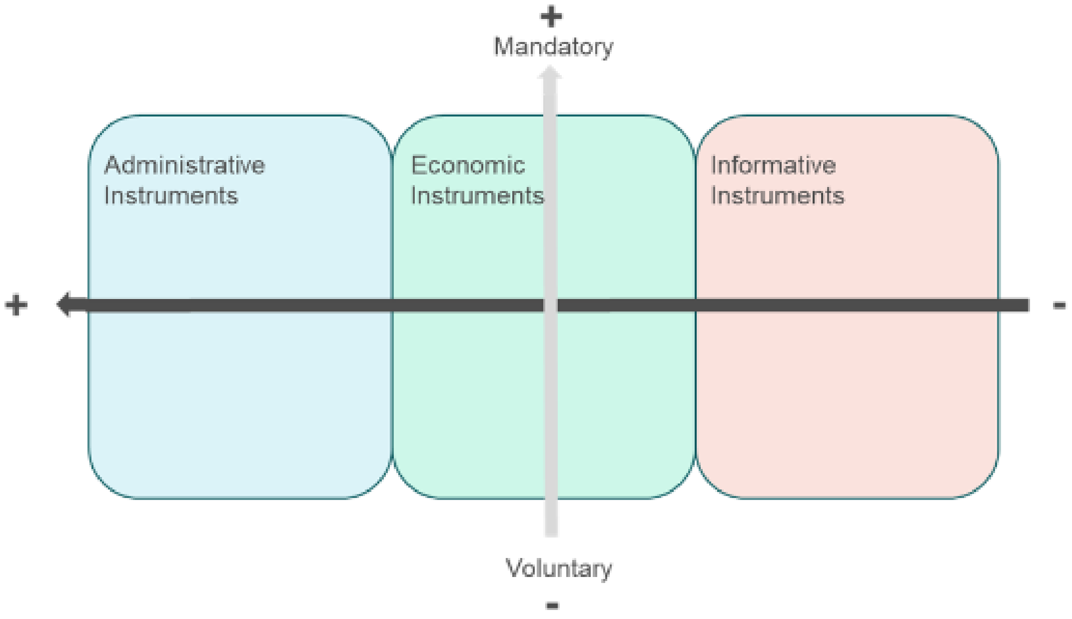
Policy instruments are the actual tools governments use to implement their policies. Policymakers have the option to select from a wide range of instruments to address a certain policy problem and achieve a desired outcome. A policy instrument constitutes a steering function and provides incentives for achieving a certain policy. Policy instruments can be divided into three types (administrative, economic, and informative) in relation to their nature and into two types (mandatory, voluntary) concerning their implementation mode (Mont & Dalhammar, 2005; Vedung, 1998). Other typologies in literature might include more than three categories and distinguish between, e.g. voluntary agreements and self-regulation as separate categories (Gunningham et al., 1998). However, the categorisation that is most consistent among policy sources is presented in **Table 4**, including also a few indicative examples of related measures per category.

Table 4. Policy instruments typology and examples of measures.

	Mandatory	**Voluntary**
Administrative	e.g. bans, standards, quotas, licences	e.g. standards, agreements between government and industry
Economic	e.g. taxes, fees, tariffs, subsidies, financial support	e.g. public procurement, loan guarantees, charges
Informative	e.g. reporting requirements, labelling, education	e.g. certification schemes, awareness raising campaigns, environmental management systems

A well-defined command and control administrative policy instrument is typically more effective than a mere informative instrument, which is mostly applied as a supportive instrument. Moreover, the potential effect of a mandatory policy instrument, under monitoring obligations by a competent authority, which is applied throughout a sector or a national context, can be more effective than a voluntary agreement between industry players and a central government authority. In **Figure 33** the potential effectiveness of policy instruments according to their typology is illustrated.

Figure 33. Anticipated effectiveness of policy instruments by type



Source: JRC elaboration

7.5.4 Epistemic uncertainty analysis on policy instruments

Additionally, the analysis of the epistemic uncertainty sheds light on the robustness of the results. While it is not the goal to create exact predictions of how CE policy will materialise in the four different worlds, understanding their main drivers and actors can support reflections around the implementation of the CE levers and corresponding policies (Muiderman et al., 2020). For policy development, the strength of the actors, their respective incentives and system configuration is essential. The expected effectiveness of the different policy instruments and corresponding technical levers are mapped out in **Table 5**. It is to be expected, that economic policy instruments are most effective in societies that have policy mixes supportive of sustainability, where the strong actors are either the governance actors on EU level or businesses. They are less effective in uncoordinated policy environments where agency lies with local communities or at member state level. Administrative instruments work best where EU governance actors are powerful actors, and less so with business and member state level agency, with the lowest effectiveness if agency is on communal level. Finally, informative instruments were considered to have medium effectiveness in all scenarios except the scenario where member states have most power and sustainability policies are not coordinated.

Table 5. Predicted effectiveness of technical levers and policy instruments in different scenarios

Type of society	**Technical CE lever**	**Economic instrument**	**Administrative instrument**	**Informative instrument**
Collectivist / not supportive of sustainability	medium	low	low	medium
Collectivist / supportive of sustainability	high	high	high	medium
Individualist / supportive of sustainability	high	high	medium	medium
Individualist / not supportive of sustainability	medium	low	medium	low

Source: JRC elaboration

This additional sensitivity analysis is an attempt to contribute to a discussion on managing uncertainties that go beyond data uncertainties into uncertainties of different realities. It is a call to scholars not to get lost in percentages of data ranges, but also conceptualising futures different from what we might think or like. In this way, this analysis provides valuable data for underpinning decision-making in an increasingly volatile world, where scenarios deviating from the historical trajectories can offer different parallel ways forward.

7.5.5 Policy suggestions for Recalibrating the Circular Economy in the EU

The policy landscape regulating the material lifecycle of cement and concrete is already well populated, with legislative and guidance documents covering all life cycle stages. As can be observed from **Table 6**. Existing and proposed policy instruments to support implementation of CE levers in the cement and concrete sector, most of the implemented and planned policy instruments related to the proposed CE levers are of informative nature, both voluntary and mandatory. The updated EU

Regulation 2024/3110 on Construction Products marketing (CPR) and EU Directive 2024/1275: Energy Performance of Buildings (EPBD) cover mainly the production and use phase of buildings, with partial attention to end-of-life. Both directives foresee policy instruments that are predominantly informative, but mandatory policy measures. In some cases, further described below, there are also administrative measures, stipulating minimum environmental performance of products. Towards the EoL, the Waste Framework Directive 2008/98/EC (WFD) proposes informative mandatory policies, while the EU construction & demolition waste management protocol, including guidelines for pre-demolition and pre-renovation audits of construction works is currently a voluntary informative document. The following paragraphs lay down the main characteristics of the relevant regulation and are followed by direct proposals of how to support the implementation of the CE levers, specified by CE clusters.

Table 6. Existing and proposed policy instruments to support implementation of CE levers in the cement and concrete sector

R-cluster	Lever	GHG reduction[18]	Existing & planned policy instruments			Additional policy instrument		
			Name	Type	Lifecycle stage	Name	Type	Lifecycle stage
Reduce	Clinker raw material substitution	-1 Mt CO_2 eq.	None	-	-	Higher landfill tax on construction and demolition (mineral) waste could divert it from landfill to co-processing, enabling the uptake of ashes into the clinker[19].	Econ.; mandatory	Prod./EoL
	Clinker substitution	-14.7 Mt CO_2 eq.	The CPR foresees a digital product passport and mandatory reporting of minimum environmental sustainability performance criteria in Declaration of Performance and conformity (DoPC) for contracts falling under GPP (Directives 2014/24/EU or 2014/25/EU)	Inform.; mandatory	all	Updating of cement standards from recipe to performance based with explicit mentioning of calcined clay (mentioned in EN 197-1 standard only indirectly under CEM II C-M)	Inform.; mandatory	Production
						Make green public procurement mandatory and include threshold for CO_2 emissions for cement in the technical specifications or award extra points in tenders to low emissions cement (e.g. through delegated acts on "Cement, Building Limes and other hydraulic binders")	Admin./Econ; mandatory	Production & use
						A labelling system (e.g. traffic light labelling) could be developed to indicate CO_2 emissions of SCMs (e.g. through a delegated act)	Informative., Mandatory	Production
						Subsidies for grinding/blending technologies of limestone	Econ.; voluntary	Production

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[18] Total annual savings calculated relative to the Baseline for year 2050 per CE lever. Take into account that the sum of the savings is larger than the actual savings of the ACE50, due to the interrelationships of the levers.

[19] Recent figures reported by JRC and EEA indicate that currently taxes on landfilling of CDW (mineral portion) are on average across EU27 around 19 EUR/t, but vary significantly depending on member state and region (e.g. from few EUR to more than 60 EUR/t).

						Subsidies for clinker alternatives from secondary raw materials (taking into account phase-out of by-products from sectors relying of fossil fuels) and calcined clay	Econ.; voluntary	Production
						Decrease taxes of low carbon construction projects	Econ.; mandatory	Production
						Fund educational campaigns on different primary and secondary SCMs as well as their potential application amongst industry professionals	Inform.; voluntary	Production
	Cement substitution	-6.6 Mt CO_2 eq.	The CPR foresees a digital product passport and mandatory reporting of minimum environmental sustainability performance criteria in Declaration of Performance and conformity (DoPC) for contracts falling under GPP (Directives 2014/24/EU or 2014/25/EU)	Inform.; mandatory	all	Updating of cement and concrete standards from recipe to performance based with explicit mentioning of alternative binders	Inform.; mandatory	Production
						Make green public procurement mandatory and include threshold for CO_2 emissions for cement in the technical specifications or award extra points in tenders for low emissions cement (e.g. through delegated acts on “Cement, Building Limes and other hydraulic binders”	Admin./Econ; mandatory	Production & use
						A labelling system (e.g. traffic light labelling) could be developed to indicate CO_2 emissions of alternative binders (e.g. through a delegated act)	Informative., Mandatory	Production
						Subsidies for cement alternatives such as sulphoaluminate cement and carbonatable calcium silicate cement to increase their uptake.	Econ.; voluntary	Production
						Decrease taxes of low carbon construction projects	Econ.; mandatory	Production
						Fund educational campaigns on alternative binders their potential application amongst industry professionals	Inform.; voluntary	Production

	Concrete substitution	+3.4 Mt CO_2 eq.	The CPR foresees a digital product passport and mandatory reporting of minimum environmental sustainability performance criteria in Declaration of Performance and conformity (DoPC) for contracts falling under GPP (Directives 2014/24/EU or 2014/25/EU)	Inform.; mandatory	all	Construction with wood only recommended when wood is locally and sustainably available due to limited GHG savings and increased material costs. No concrete policy proposed.	-	Use
						Decrease taxes of low carbon construction projects	Econ.; mandatory	Production
	Cement reduction	-1.4 Mt Mt CO_2 eq.	The CPR foresees a digital product passport and mandatory reporting of minimum environmental sustainability performance criteria in Declaration of Performance and conformity (DoPC) for contracts falling under GPP (Directives 2014/24/EU or 2014/25/EU)	Inform.; mandatory	all	Make green public procurement mandatory and include threshold for CO_2 emissions for cement in the technical specifications or award extra points in tenders for low emissions cement (e.g. through delegated acts on “Cement, Building Limes and other hydraulic binders” or “Products related to concrete, mortar and grout”)	Admin./Econ; mandatory	Production & use
						Updating of cement and concrete standards from recipe to performance based	Inform.; mandatory	Production
						Decrease taxes of low carbon construction projects	Econ.; mandatory	Production
	Concrete reduction	-14.4 Mt CO_2 eq.	The CPR foresees a digital product passport and mandatory reporting of minimum environmental sustainability performance criteria in Declaration of Performance and conformity (DoPC) for contracts falling under GPP (Directives 2014/24/EU or 2014/25/EU)	Inform.; mandatory	all	Updating building standards to performance based, as to prevent over-use of concrete	Inform.; mandatory	Production
						Make green public procurement mandatory and include threshold for CO_2 emissions for concrete in the technical specifications or award extra points in tenders for low emissions concrete (e.g. through delegated acts on “Precast normal/ lightweight/ autocaved aerated concrete products” or “Products related to concrete, mortar and grout”)	Admin./Econ; mandatory	Production & use

						Decrease taxes of low carbon construction projects	Econ.; mandatory	Production
Reuse	Lifetime increase	-8.0 Mt CO_2 eq.	The Revised Energy Performance of Buildings Directive (EPBD) promotes deep renovation and design for reconstruction, which is facilitated by a renovation passport and national plans for assessing GHG emissions, minimum energy performance standards and harmonised building codes	Inform.; mandatory	all	Financial support by Member States in the form of subsidies and tax breaks for renovation of buildings with a focus on vulnerable households	Econ.; voluntary	Use
						Tax on demolition, to incentivise the reuse of structural elements for deep renovation	Econ.; mandatory	EoL
	Concrete reuse	-0.4 Mt CO_2 eq.	The CPR foresees a digital product passport and mandatory reporting of minimum environmental sustainability performance criteria in Declaration of Performance and conformity (DoPC) for contracts falling under GPP (Directives 2014/24/EU or 2014/25/EU)	Inform.; mandatory	all	Use digital product passport for evaluation of reuse at end of life, i.e. a certain degree of modularity, including the management of insurance issues related to the second life cycle (e.g. through delegated act on Precast normal/ lightweight/ autocaved aerated concrete products)	Inform.; mandatory	all
			The Revised Energy Performance of Buildings Directive (EPBD) promotes deep renovation and design for reconstruction, which is facilitated by a renovation passport and national plans for assessing GHG emissions, minimum energy performance standards and harmonised building codes.	Inform.; mandatory	all	Pre-demolition audits with mandatory use of EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works (e.g. through inclusion in GPP tendering process)	Inform.; mandatory	EoL
			EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works	Inform.; voluntary	all	Tax on demolition, to incentivise the reuse of pre-cast elements on or off-site	Econ.; mandatory	EoL
						Tax breaks on selective demolition	Econ.; voluntary	EoL
						Increased landfill taxes for construction and demolition waste (e.g. in Waste Framework Directive)	Econ.; mandatory	EoL

Recover	Recycle concrete to clinker raw material and cement	-2.5 Mt CO_2 eq. (clinker raw material) + -1.4 Mt CO_2 eq. (cement)	The CPR foresees a digital product passport and mandatory reporting of minimum environmental sustainability performance criteria in Declaration of Performance and conformity (DoPC) for contracts falling under GPP (Directives 2014/24/EU or 2014/25/EU)	Inform.; mandatory	all	Make green public procurement mandatory and include threshold for CO_2 emissions for cement in the technical specifications or award extra points in tenders for low emissions cement with recycled content (e.g. through delegated acts on “Cement, Building Limes and other hydraulic binders” or “Products related to concrete, mortar and grout”)	Inform.; mandatory	all
			The Revised Energy Performance of Buildings Directive (EPBD) promotes deep renovation and design for reconstruction, which is facilitated by a renovation passport and national plans for assessing GHG emissions, minimum energy performance standards and harmonised building codes.	Inform.; mandatory	all	Pre-demolition audits with mandatory use of EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works (e.g. through inclusion in GPP tendering process)	Inform.; mandatory	EoL
			EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works	Inform.; voluntary	all	Tax breaks on selective demolition	Econ.; voluntary	EoL
						Subsidise research and scale up of fine grinding recycling solutions to win high quality cement fines from CDW concrete	Econ.; voluntary	EoL
						Facilitate partnership between cement & CDW companies to create transparency on composition of recycled materials in situ	Inform.; voluntary	EoL
						Fund educational campaigns on different recycled materials and their properties amongst industry professionals	Inform.; voluntary	EoL/Production
	Recycle concrete to aggregates	+0.1 Mt CO_2 eq.	The CPR foresees a digital product passport and mandatory reporting of minimum environmental sustainability performance criteria in Declaration of Performance and conformity	Inform.; mandatory	all	Pre-demolition audits with mandatory use of EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works	Inform.; mandatory	EoL

			(DoPC) for contracts falling under GPP (Directives 2014/24/EU or 2014/25/EU)			(e.g. through inclusion in GPP tendering process)		
			The Revised Energy Performance of Buildings Directive (EPBD) promotes deep renovation and design for reconstruction, which is facilitated by a renovation passport and national plans for assessing GHG emissions, minimum energy performance standards and harmonised building codes.	Inform.; mandatory	all	Tax breaks on selective demolition	Econ.; voluntary	EoL
			EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works	Inform.; voluntary	all	Increased landfill taxes for construction and demolition waste (e.g. via implementation of Waste Framework Directive)	Econ.; mandatory	EoL
			Waste Framework Directive is specifying End of Waste Criteria for aggregates to facilitate market creation	Inform.; mandatory	EoL	Create cross-financing mechanism from levy for primary aggregates to concrete recycling technologies	Econ.; mandatory	Production
						Fund campaigns on different recycled materials and their properties amongst industry professionals	Inform.; voluntary	EoL/Production

Source: JRC elaboration

Construction Products Regulation (CPR)

The CPR has a similar function for construction products that the Ecodesign for Sustainable Products Regulation (ESPR) has for the energy-intensive goods it covers. For certain product categories falling under the requirement of Green Public Procurement criteria, a set of environmental minimum performance requirements will need to be met. These are going to be stipulated by delegated acts on materials, which is where we encourage policy makers to take into account the findings of this study. Relevant Delegated Acts are envisioned for *Precast normal/ lightweight/ autocaved aerated concrete products; Cement, Building Limes and other hydraulic binders; Masonry and related products; Aggregates* and *Products related to concrete, mortar and grout.* It is into these delegated acts that we propose to include Product requirements that are in line with our levers, which will ultimately be applicable for the Declaration of Performance and Conformity (DoPC). The CPR mandates this DoPC must include the product's environmental sustainability performance over its life cycle (with a range of impact categories related to the PEF phased in between 2026 and 2032), specifically in relation to predetermined environmental essential characteristics. It is to be mandatory for all construction projects where contracts require minimum environmental sustainability performance for construction products covered by harmonised technical specifications, i.e. Green Public Procurement (under Directives 2014/24/EU or 2014/25/EU). Under the CPR, construction products need to develop a digital product passport, including, amongst other impacts the environmental impacts, with a focus on climate change mitigation. By regulating the implementation of the digital passport in the product-specific delegated acts and managing the information therein, the legislation automatically enables more traceability of materials and their impacts and creates connections between the value chain actors.

Directive on Energy Performance in Buildings (EPBD)

The EPBD requires large new buildings from 2028 and all new buildings from 2030 onwards to publish the life cycle global warming potential. While it technically covers the whole life cycle and thus its mainly informative policy instruments could be informed by all our levers, the focus lies on the use phase and end of life phase of buildings. The EPBD foresees national building renovation plans that are supposed to reduce GHG emissions throughout the whole lifecycle, minimum energy performance standards and building codes. Moreover, member states can provide financial support in the form of subsidies and tax breaks for renovation of buildings in the form of state aid, with a focus on vulnerable households. Energy certificates inform about the energy efficiency of buildings and voluntary building renovation passports provide a roadmap for renovations in terms of energy performance, circularity of the building, and reduction of GHG emissions. Finally, awareness campaigns are also stipulated to sensitise buildings owners and tenants on the issue of energy performance. Besides prioritising the prevention of demolition, national building renovation plans state that policies should include ways to increase modularity of buildings, i.e. allowing for reuse of precast elements. Moreover, policies are required to enable high-quality treatment of CDW, implying separate collection and the financing of recycling technologies.

Waste framework directive

Whereas the CPR and EPBD are mainly covering the production and use phase of buildings, with partial focus on end-of-life, the WFD focuses on EoL only. Though there are currently no targets for construction and demolition waste in place that are not already fulfilled, the updated legislation foresees End-of-Waste (EoW) criteria for aggregates, which are intended to facilitate the creation of a European market for secondary aggregates. As several countries already have EoW criteria and markets of recycled aggregates in place, (also linked to local scarcity of materials and the cost of transport), about 8% of all aggregates used are currently recycled (Pacheco et al., 2023).

7.5.5.1 Policies supporting the Reduce cluster

The main relevant policy framework in this regard is the CPR, with its options to further specify minimum sustainability performance criteria in the DoPC, in connection with the Directives 2014/24/EU or 2014/25/EU regulating the applicability of GPP. With both informative and administrative elements, this legislation has the potential to support several levers at once.

In addition to the existing policies, a broader set of policies is proposed. While several GPP criteria exist for buildings, most of them are of voluntary nature. An option is to make GPP mandatory for public procurement contracts and explicitly include low-emissions cement and/or concrete in GPP criteria with their explicit mentioning (especially solutions with calcined clay or alternative binders such as sulphoaluminate cement and carbonatable calcium silicate) (Agora Industry, 2022; Mission Possible Partnership, 2023). This would address levers 2-6, with the exception of lever 4 (substitution with wood) which should be evaluated on a case-by-case basis. Therefore, GPP criteria could specify both project-and material-level emissions-reduction thresholds (especially for cement) and targets to ensure material efficiency improvements (Agora Industry, 2022; Mission Possible Partnership, 2023). These targets could be mandatory (as technical specifications) or ensure the higher scoring as award criteria in public tenders (Favier et al., 2018). Another option to increase the demand for low-carbon concrete are maximum embodied carbon in concrete or the structural foundation of the building, which should decrease over time. However, before such a step can be implemented, the reporting on GWP first needs to become standardised (as is planned by 2030 for new buildings in the EPBD).

Besides GPP, the sparse use of blended cements and overuse of both cement and concrete can be countered by replacing the recipe-based standards for cement and concrete with performance-based standards (Mission Possible Partnership, 2023; Nilsson et al., 2020)). This implies changes in the composition of cement, as well as a reduction of the use of cement in concrete mixtures, as long as they fulfil their structural function (lever 2 and 5). Moreover, the overuse of concrete itself due to standardised values of civil engineering offices can be reduced by adhering more strictly to building standards (lever 6) (IEA, 2019). While this shift is already ongoing, it is essential to stay in line with the CPR regulation and the therein defined delegated acts (Marmier, 2023). As to expedite market access to innovative types of cement, the CE label under the CPR could be assigned after undergoing the European Technical Assessment (ETA) procedure (Agora Industry, 2022; Marmier, 2023). It should then be considered compliant on national level, except if the member states object.

Given the large upfront investments necessary for retrofitting cement kilns and temporary losses in productivity, policies should offer financial incentives and subsidies for research and upscaling of better grinding techniques and novel cement, such as LC3 or other low-carbon cements (excluding reductions achieved through CCS) (Favier et al., 2018; Nilsson & Verschaeve, 2023). An option for these are Horizon projects for research and specific mentioning of low carbon cement in the EU taxonomy and/or the multiannual financial framework (MFF) (Agora Industry, 2022). These low hanging fruits should receive as much attention from investors as the industry-driven quest for financing CCS and hydrogen, which are at the risk of perpetuating the status quo and causing a CO_2 technology lock-in (Habert et al., 2020; Watari et al., 2022).

Moreover, several scholars have underlined the importance of strengthening actor networks along the value chain and educating key players on novel, low-carbon materials, as well as material efficiency. Designers, engineers, architects, local contractors as well as construction workers are to be trained in their understanding of optimised material use throughout construction projects (IEA, 2019; Mission Possible Partnership, 2023; Schüwer et al., 2024). Finally, public authorities at all levels are to be instructed on the proposed GPP criteria to support local businesses accordingly.

7.5.5.2 Policies supporting the Reuse cluster

In addition to the CPR, the Reuse cluster is strongly affected by the EPBD, given its focus on energy-efficient lifetime extension of buildings. The digital product passport of the CPR as well as the proposed renovation passport under the EPBD can both contain critical information that enable judgement on the suitability of lifetime extension of buildings, structural elements (lever 7) or reuse of pre-cast concrete elements (lever 8) (Knoth et al., 2022). In the case of reuse, additionally, the EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works is of importance to guide the selective demolition process.

To build on the current framework, the CPR plans a delegated act on *Precast normal/ lightweight/ autocaved aerated concrete products,* where the option of reuse at end of life, i.e. a certain degree of modularity, including the management of insurance issues related to the second life cycle should be made explicit (lever 8) (Material Economics, 2018). Moreover, a policy instrument covering the Reuse cluster that aims towards the prevention of demolition, such as a tax on full demolition, is proposed (agnostic to the policy framework). For lever 8 (reuse of pre-cast concrete elements) additional instruments such as the mandated use of the selective demolition, where the EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works is set as a mandatory document to follow, and increased landfill taxes are proposed. These instruments will be described more in detail in the following section.

7.5.5.3 Policies supporting the Recover cluster

As recycling affects all product life cycle stages directly or indirectly, the relevant policy documents are the CPR, EPBD, the selective-demolition guidelines as well as the WFD. The digital product passport is also of importance for recycled materials that are used either in clinker raw meal (L9), cement (L10) and concrete (L11), as one of the main reasons for not using recycled cement fines is their variable composition. This transparency can create trust between supply chain actors, as e.g. CDW companies can inform cement producers in advance about the composition of cement fines in their area, enabling long-term planning of production with secondary materials (Dewald & Achternbosch, 2016; Favier et al., 2018; Pacheco et al., 2023). Moreover, the national renovation plans by the EPBD are required to enable high-quality treatment of C&DW, implying separate collection and the financing of recycling technologies such as wet recycling, ADR and even HAS (levers 9-10).

In the specification of the delegated acts of the CPR, the product groups Cement, Building Limes and other hydraulic binders, Masonry and related products, Aggregates and Products related to concrete, mortar and grout could designate performance classes that include recycled cement fines and rank this significantly higher than recycled aggregates, from an environmental perspective (Enengel et al., 2023). It is crucial to not simply set a recycled content target for concrete, as this could be fulfilled by recycled aggregates, with limited environmental benefits. Instead, the minimum sustainability performance criteria relevant for the GPP should focus on the substitution of clinker and cement with (primary or secondary) SCMs or alternative binders, respectively (lever 2, 3, 9, 10). While these measures mostly affect the construction phase, GPP can also create a pull-effect for more sustainable demolition practices at the EoL. When demolishing old buildings for newly procured projects, GPP should mandate the use of pre-demolition audits using the EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works (Damgaard et al., 2022; Pacheco et al., 2023). Moreover, the use of traditional demolition should be justified and contractors offering to work with CDW companies that employ selective demolition practices should be preferred, e.g. with higher scores in tenders. Regarding the WFD, the European EoW criteria are expected to increase the use of recycled aggregates, a trend that can further be augmented by mandating selective demolition, where possible. Given that there is currently no market for recycled cement fines, even though their importance in terms of environmental impact is actually higher than that of aggregates, there are no EoW criteria planned. Instead, other types of financial policy instruments are proposed below.

They include higher landfill taxes for inert mineral waste, which encourage recycling of concrete waste and thus indirectly support selective demolition (Favier et al., 2018; Material Economics, 2019). Moreover, the aforementioned Horizon funding vehicle should also target the EoL of concrete, with a focus on recovering cement fines for replacing cement or clinker raw materials, given the higher environmental benefits when compared to recycling of concrete to aggregates (Caro et al., 2024; Pacheco et al., 2023).

Finally, similarly to the other CE clusters, educational campaigns for industry practitioners on the existence and application of secondary raw materials as well as related standards (with a focus on cement fines, given the wider awareness – though with strong regional variation - of recycled aggregates) should be supported (Pacheco et al., 2023). In addition, public authorities at all levels are to be trained in understanding the proposed GPP criteria regarding EoL and secondary materials, as well as the new secondary markets created by the EoW criteria of aggregates, to support local businesses accordingly (Pacheco et al., 2023).

7.5.5.4 Policies supporting further research on demand levers

Finally, the frequently mentioned demand side reduction requires more dedicated research, given the intricate relationship with considerations of affordable housing and income redistribution. Therefore, Horizon funds could finance such interdisciplinary research covering the economic, sociological and technical angles of the problem, going beyond technical minimum requirements of living space to more equitable solutions.

8 Conclusions

This study has investigated the potential of circular economy (CE) levers to mitigate climate change, reduce resource dependency, and promote socio-economic benefits in the EU cement and concrete sector. The results indicate that the implementation of CE levers can lead to significant reductions in GHG emissions, primary material demand, and waste generation. The study highlights the importance of a holistic approach to CE, considering the entire life cycle of cement and concrete and the interactions between different stakeholders and sectors.

8.1 Key scientific findings

The analysis suggests that the combined application of the CE levers studied can achieve an additional impact reduction on climate change of between 38-52 Mt CO_2-eq. annually in 2050, on top of what would be achieved by decarbonisation of the energy system only. The results also show that CE can lead to a decrease in the EU demand for fossil resources (e.g., crude oil and natural gas) for energy. It implies a decrease of 1.6% in electricity and 0.2% decrease in fossil fuel-based energy, with the highest decreases in natural gas, relative to the Baseline by 2050. In addition to a decrease in fossil-based energy necessary for production, there is a decrease of EUR 6.3 billion in imports due to a lower material demand, when compared to a scenario reflecting only decarbonisation. These imports reductions result an increase of the EU trade balance, estimated at EUR 6.1 billion, indicating a slight decrease in exports by EUR 0.2 billion. However, these changes come also with some observed decreases in Gross Value Added, Gross Domestic Product, and employment in the affected cement and concrete sector, with notable spillovers in the construction sector. While those are expected because of the reduction in material demanded by the industry, it emphasises the need for further research on the CE implications on the service (e.g. repair) sectors. In this study, a simplified, but commonly used approach was followed, whereby the reductions in economic input demanded by a sector were diverted to waste management and innovation. However, this 1:1 reallocation of resources may in reality be very different and deserves further investigation.

Moreover, the study underlines the importance of a policy mix approach, combining different policy instruments to address the complex challenges of CE along the material life cycle. The study suggests a range of policy instruments to activate the CE levers, including mandatory and voluntary measures, such as administrative, economic, and informative instruments. Recommendations include measures to reduce the use of cement and concrete through substitution and more efficient design, extend product lifetime and use, and recover materials at the end of life effectively, with a focus on winning back cement fines.

In conclusion, this study demonstrates the potential of CE to contribute to a more sustainable and resource-efficient cement and concrete sector in the EU. The implementation of CE levers can lead to significant environmental benefits, but requires a holistic approach, careful policy design, and coordination among stakeholders.

8.2 Key policy recommendations

The following policy recommendations are suggested to support the implementation of the CE levers in the EU cement and concrete sector, beyond what currently is applied in the EU, with the goal of reducing clinker use, promoting sustainable use of materials, and minimising CDW.

- ***Reduce*** (reducing use of clinker, cement and concrete):

  - Make green public procurement mandatory and include threshold for CO_2 emissions for cement and concrete in the technical specifications or award extra points in tenders to low emission cement/alternative binders
  - Develop a labelling system (e.g. traffic light labelling) to indicate CO_2 emissions of SCMs
  - Financial support for grinding/blending technologies of limestone, calcined clay and other clinker alternatives from secondary raw materials (taking into account phase-out of by-products from sectors relying of fossil fuels)
  - Financial support for cement alternatives such as sulphoaluminate cement and carbonatable calcium silicate cement to increase their uptake
  - Tax breaks for low carbon and circular construction projects
  - Updating of cement, concrete and building standards from recipe/process to performance based
  - Funding of educational campaigns on different primary and secondary SCMs and alternative binders, as well as their potential application amongst industry professionals
  - Construction with wood only recommended, when wood is locally and sustainably available due to limited GHG savings and increased material costs. No concrete policy proposed.
- ***Reuse*** (extending lifetime of buildings)
  - Use digital product passport for evaluation of reuse at end of life, i.e. a certain degree of modularity, including the management of insurance issues related to the second life cycle
  - Tax on demolition, to incentivise the reuse of structural elements for deep renovation and reuse of pre-cast elements
- ***Recover*** (improving recycling rate and quality):
  - Make green public procurement mandatory and include threshold for CO_2 emissions for cement in the technical specifications or award extra points in tenders for low emissions cement with recycled content
  - Financial support for research and scale ups of fine grinding recycling solutions to win high quality cement fines from CDW concrete
  - Mandate pre-demolition audits with mandatory use of EU construction & demolition waste management protocol including guidelines for pre-demolition and pre-renovation audits of construction works (e.g. through inclusion in GPP tendering process)
  - Tax breaks on selective demolition
  - Increased landfill taxes for construction and demolition waste and mixed waste, to increase co-processing, enabling the uptake of ashes into the clinker
  - Create cross-financing mechanism from levy for primary aggregates to concrete recycling technologies

    - Facilitate partnership between cement & CDW companies to create transparency on composition of recycled materials in situ
    - Fund educational campaigns on different recycled materials and their properties amongst industry professionals

8.3 Future research directions

The study identifies several limitations and challenges to be addressed by further research, notably:

- **Economic growth of service sector**: this study takes simplified assumptions on the effects of CE levers on service sectors, such as repair. We encourage the analysis of the implications of CE levers on repair and similar service activities as well as research and innovation activities in detail. This may also be done by employing Input-Output analysis or dynamic macroeconomic models such as FIDELIO. However, the focus should specifically be on the socio-economic consequences in service sectors, in terms of trade, growth, and employment change, as a response to selected CE lever implementation.
- **Demand-based levers**: this study only partially assessed the consequences of consumer demand-based levers (for the steel sector). The motivation to discard such levers is mainly related to the fact that many of these imply a behavioural change and a potential limitation of individual freedom. Additional research should explore the socio-economic implications of changing consumer's behaviour towards different or reduced consumption, i.e. focusing on sufficiency. The authors are aware of an ongoing study on these aspects carried out by Cambridge Econometrics on behalf on DG CLIMA.
- **Quality of recycling**: this study investigates the effects of steel scrap quality changes on resource and environmental benefits in detail. However, assessing the effects of changes in recycled material quality is subject to uncertainties, because of the underlying approach used to model such effects as well as the possible market-triggered implications. Further research is encouraged on this topic, notably on macroeconomic effects.
- **Strengthening integration of bottom-up and top-down methods**: this study strengthens the link between bottom-up (MFA, LCA) and top-down (EE-MRIO, dynamic macroeconomic modelling) methods in several ways, notably by disaggregating the Eurostat compliant FIGARO-E3 Input-Output tables in accordance with detailed sector-specific material flow analyses and life cycle inventory datasets. Moreover, the life cycle inventories from the LCA were used as input for the EE-MRIOA cement and concrete sector, and the growth path of EEIO and FIDELIO were aligned according to the GECO 2023 projections. However, the four sectors were analysed separately, whereas, ideally, the assessment would integrate the four sectors into one dynamic macroeconomic model in FIDELIO.
- **Prospective assessment on demand-shocks**: this study is the first that the authors are aware of to illustrate the trade effects of CE levers. However, in view of the ongoing geopolitical landscape characterised by tariffs and trade wars, we encourage research looking at extreme scenarios identified through foresight tools, e.g. in terms of drastic changes to trade relationships, 'buy EU' requirements, GDP growth, or energy scenarios (e.g. use FIDELIO to model the selective application of tariffs to distort current market prices, affecting trade partnerships and final consumer goods prices).

- **Implementation of the levers via policy**: this study focuses on the impacts of CE levers and does not detail how to concretely implement them in policy or on the transition pathways required to achieve a full-fledge CE implementation. The former is a typical objective of impact assessment supporting studies, which identify appropriate policy measures (and options) to enable the CE levers, assess administrative costs (on top of compliance ones, which are partially captured in this study), and quantify distributional effects across affected income groups. Studying transitional pathways requires instead dedicated foresight analyses that help mapping the chronology and related interdependence of CE lever implementation.

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List of abbreviations and definitions

Abbreviations	Definitions
ACE50	Ambitious Circular Economy scenario (2050)
ADR	Advanced Dry Recovery
BSL50	Baseline scenario (2050)
CAPEX	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CE	Circular Economy
CEAP	Circular Economy Action Plan
CFF	Circular Footprint Formula
CGE	Computable General Equilibrium
CMUR	Circular Material Use Rate
CPR	Construction Products Regulation
CRM	Critical Raw Material
DA	Delegated Act
DRS	Deposit Return System
EC	European Commission
ECO50	Eco-States scenario (2050)
EEIOA	Environmentally Extended Input-Output Analysis
EE-MRIO	Environmentally Extended Multi Regional Input-Output
EF	Environmental Footprint
eLCC	Environmental Life Cycle Costing

Abbreviations	Definitions
EPR	Extended Producer Responsibility
ESPR	Ecodesign for Sustainable Products Regulation
ETS	Emissions Trading System
EU	European Union
feLCC	Full Environmental Life Cycle Costing
GBB50	Green Business Boom scenario (2050)
GDP	Gross Domestic Product
GECO	Global Energy and Climate Outlook
GEW50	Glocal Eco-World scenario (2050)
GHG	Greenhouse Gas
GPP	Green Public Procurement
GRO50	Growth-oriented baseline scenario (2050)
GTC50	Greening through Crisis scenario (2050)
GVA	Gross Value Added
HAS	Heating Air classification System
IA	Implementing Act
IAM	Integrated Assessment Model
IOA	Input-Output Analysis
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
ME	Macroeconomic analysis
MFA	Material Flow Analysis

Abbreviations	Definitions
Mt	Megatonne
NDC-LTS	Nationally Determined Contribution - Long-Term Strategies
OPEX	Operating costs
PJ	Petajoule
PPWR	Packaging and Packaging Waste Regulation
ROW/RoW	Rest of the World
SCM	Supplementary cementitious materials
SHR50	Shrink-oriented baseline scenario (2050)
SME	Small and medium-sized enterprises
STQ21	Status Quo scenario (2021)
SUT	Supply and Use Tables
WEEE	Waste from Electrical and Electronic Equipment
WFD	Waste Framework Directive

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Annexes

Annex 1. Data sources for MFAs

Table A 1. Data sources for Material Flow Analyses in Section 3

Material flow	Data source
Clinker raw materials	Calibrated to use of clinker in cement, from Ecoinvent 3.9.1 – Market for clinker – Europe without Switzerland
Share of cements	CEMBUREAU (2021), Georgiades et al. (2023) and Nilsson et al. (2020)
CEM I	EPD, CEMBUREAU (2020)
CEM II	EPD, CEMBUREAU (2020)
CEM III	EPD, CEMBUREAU (2020)
CEM generic	Ecoinvent 3.9.1 with clinker ratio of 77%
CEM low carbon	Avet & Scrivener (2018)
Alternative binders	Based on composition of Miller & Meyers (2020)
Aggregates	Based on composition of concrete (see below)
Share of concrete	Based on use of cement from CEMBUREAU (2021)
Ready-mixed concrete	Ecoinvent 3.9.1, comparison with ERMCO (2019)
Pre-cast concrete	Korander & Mannonen (2015), Ecoinvent 3.9.1
Plasters & mortar	Thamboo et al. (2019), Ecoinvent 3.9.1
Share in construction	Based on use of cement by Favier et al. (2018)
Buildings	Share of concrete types from ERMCO (2019) and BIBM consultation
Infrastructure	Share of concrete types from ERMCO (2019) and BIBM consultation
Maintenance	Share of concrete types from ERMCO (2019) and BIBM consultation
Concrete from demolition	Damgaard et al. (2022) and Cristobal et al. (2023)
Share of selective vs. traditional demolition	Assumption based on stakeholder consultation
Reuse	Pristerà et al. (2024) and Cristóbal García et al. (2024)
Recycling	Caro et al. (2024) and Damgaard et al. (2022)
Backfilling	Caro et al. (2024) and Damgaard et al. (2022)
Landfilling	Caro et al. (2024), Damgaard et al. (2022) and Iodice et al. (2021)
Share of recycling technologies	Own assumption with consultation of industry and academic literature
Share of low quality recyclate for backfilling	Caro et al. (2024)
Share of recycled concrete aggregates from wet process	Zhang et al. (2019)
Share of recycled concrete aggregates from ADR & HAS process	Zhang et al. (2019)

Source: JRC elaboration

Annex 2. Circularity levers

This section outlines the method employed to define circularity levers in the EU cement and concrete sector. It consisted of four main steps: system boundaries definition, lever identification, lever validation, and lever quantification.

Step 1: System boundary and scope of research

The first step was to define the system boundaries for the analysis. These were set by considering all the stages of the material supply chain (from mining to waste management - see **Figure 1**), with a focus on the relevance for the EU cement and concrete sector. To this end, the scope of the analysis was mainly focused on technological interventions available to EU industry, defined according to former scientific work in support of EU policy (Cristóbal García et al., 2024; Marmier, 2023; Pacheco et al., 2023; Zibell et al., 2022) and recent reports by research consultants on their circularity relevance (Material Economics, 2018, 2019; Mission Possible Partnership, 2023; Nilsson et al., 2020). This was complemented by consultations with experts both on material sciences and industry players such as aggregate recyclers, CEMBUREAU, the European association for cement, the Federation of the European Precast Concrete Industry, as well as the European Ready Mixed Concrete Organisation. The affected industry is mainly the construction sector.

Step 2: Lever identification

The second step was the identification of circularity levers relevant for the EU cement and concrete sector. To this end, both scientific and grey literature were consulted. Selected grey literature included relevant reports on EU cement and concrete and its circularity developed over the past 6 years, provided by experts from the cement and concrete industry, consultancy firms, and policy-making. This ensured a sense of technical feasibility of the proposed solutions and provided a first idea of the market uptake of the levers. Scientific literature included peer reviewed journal articles, conference proceedings and academic dissertations. The papers were then selected based on the relevance of information regarding a specific lever, number of citations and availability of quantified results that could be employed within the modelling. A list with all the literature sources used for the identification of circularity levers for cement and concrete in the EU is provided in **Table A 2**.

Table A 2. Literature sources for the identification of circularity levers for cement and concrete in the EU

Author	Year	Title	Source type
Aggregates Europe	2022	Sustainable supply of aggregates in Europe	Industry report
Agora Industry & Material Economics	2023	Mobilising the circular economy for energy intensive materials	Industry report
Agora Industrie & SYSTEMIQ	2023	Resilienter Klimaschutz durch eine zirkuläre Wirtschaft. Perspektiven und Potenziale für energieintensive Grundstoffindustrien	Industry report
Andersen et al.	2022	Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon	Scientific journal
Barbhuiya et al.	2023	Properties, compatibility, environmental benefits and future directions of limestone calcined clay cement (LC3) concrete: A review	Scientific journal

Barbhuiya et al.	2024	Decarbonising cement and concrete production: Strategies, challenges and pathways for sustainable development	Scientific journal
Bayram & Greiff	2023	Life cycle assessment on construction and demolition waste recycling: a systematic review analyzing three important quality aspects	Scientific journal
Bostanci et al.	2018	Use of recycled aggregates for low carbon and cost effective concrete construction	Scientific journal
Caro et al.	2024	Environmental and socio-economic effects of construction and demolition waste recycling in the European Union	Scientific journal
Charef et al.	2022	The transition to the circular economy of the construction industry: Insights into sustainable approaches to improve the understanding	Scientific journal
Cavalett et al.	2024	Paving the way for sustainable decarbonization of the European cement industry	Scientific journal
CEMBUREAU	2020	Cementing the European Green Deal	Industry report
CEMBUREAU	2023	Activity report 2022	Industry report
CEMBUREAU	2024	From Ambition to Deployment	Industry report
Circular Buildings Coalition	2024	Four Circular Building Pathways towards 2050	Industry report
Clavier et al.	2020	Opportunities and challenges associated with using municipal waste incineration ash as a raw ingredient in cement production – a review	Scientific journal
Colangelo et al.	2021	Comparative environmental evaluation of recycled aggregates from construction and demolition wastes in Italy	Scientific journal
Cristóbal García et al.	2024	Techno-economic and environmental assessment of construction and demolition waste management in the European Union	Policy report
Devènes et al.	2024	Reusability assessment of reinforced concrete components prior to deconstruction from obsolete buildings	Scientific journal
Diliberto et al.	2017	Valorisation of recycled concrete sands in cement raw meal for cement production	Scientific journal
Enengel et al.	2023	Determining the recycled content in cement: A study of Austrian cement plants	Scientific journal
European Commission & Fraunhofer ISI	2024	Role of the circular economy as a contributor to industry decarbonisation beyond 2030	Policy report
Favier et al.	2018	A SUSTAINABLE FUTURE FOR THE EUROPEAN CEMENT AND CONCRETE INDUSTRY- Technology assessment for full decarbonisation of the industry by 2050	Industry report
Fort & Cerný	2020	Transition to circular economy in the construction industry: Environmental aspects of waste brick recycling scenarios	Scientific journal
Fundación CEMA	2023	CO-PROCESSING Material recovery of the mineral fraction from Refuse-Derived Fuels in the cement industry	Industry report
García-Gutierrez et al.	2023	Environmental and socio-economic sustainability of waste lubricant oil management in the EU	Policy report

Gartner & Sui	2018	Alternative cement clinkers	Scientific journal
GCCA	2022	Concrete Future - The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete	Industry report
Gebremariam et al.	2020	Innovative technologies for recycling End-of-Life concrete waste in the built environment	Scientific journal
Georgiades et al.	2023	Prospective life cycle assessment of European cement production	Scientific journal
GIZ-LafargeHolcim	2020	Guidelines on Pre- and Co-processing of Waste in Cement Production Use of waste as alternative fuel and raw material	Industry report
Griffiths et al.	2023	Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options	Scientific journal
Habert et al.	2020	Environmental impacts and decarbonization strategies in the cement and concrete industries	Scientific journal
Hansen et al.	2024	Environmental consequences of shifting to timber construction: The case of Denmark	Scientific journal
Illankoon & Vithanage	2023	Closing the loop in the construction industry: A systematic literature review on the development of circular economy	Scientific journal
Iodice et al.	2021	Sustainability assessment of Construction and Demolition Waste management applied to an Italian case	Scientific journal
IEA & WBCSD	2018	Technology Roadmap - Low-Carbon Transition in the Cement Industry	Industry report
Knoth et al.	2022	Barriers, success factors, and perspectives for the reuse of construction products in Norway	Scientific journal
Krour et al.	2020	Incorporation rate of recycled aggregates in cement raw meals	Scientific journal
Le & Bui	2020	Recycled aggregate concretes – A state-of-the-art from the microstructure to the structural performance	Scientific journal
Mañosa et al.	2024	Research evolution of limestone calcined clay cement (LC3), a promising low-carbon binder – A comprehensive overview	Scientific journal
Marmier	2023	Decarbonisation options for the cement industry	Policy report
Material Economics	2018	The circular economy—A powerful force for climate mitigation	Industry report
Material Economics	2019	Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry	Industry report
Miller & Moore	2020	Climate and health damages from global concrete production	Scientific journal
Miller & Myers	2020	Environmental Impacts of Alternative Cement Binders	Scientific journal
Mission Possible Partnership	2023	Making Net-Zero Concrete and Cement Possible: An industry-backed, 1.5°C-aligned transition strategy	Industry report
Moreno-Juez et al.	2020	Treatment of end-of-life concrete in an innovative heating-air classification system for circular cement-based products	Scientific journal
Moschen-Schimek et al.	2023	Critical review of the recovery rates of construction and demolition waste in the European Union – An analysis of influencing factors in selected EU countries	Scientific journal

Muñoz et al.	2023	Exploring the environmental assessment of circular economy in the construction industry: A scoping review	Scientific journal
Müller et al.	2024	Decarbonizing the cement industry: Findings from coupling prospective life cycle assessment of clinker with integrated assessment model scenarios	Scientific journal
Nilsson et al.	2020	Decarbonisation pathways for the EU cement sector: Technology routes and potential ways forward	Industry report
Nilsson & Verschaeve	2023	Clinker Substitution in the EU Cement Sector	Industry report
Nußholz et al.	2019	Circular building materials: Carbon saving potential and the role of business model innovation and public policy	Scientific journal
Olssen et al.	2023	Near-term pathways for decarbonizing global concrete production	Scientific journal
Pacheco & de Brito	2021	Recycled Aggregates Produced from Construction and Demolition Waste for Structural Concrete: Constituents, Properties and Production	Scientific journal
Pacheco et al.	2023	Use of recycled aggregates in concrete: opportunities for upscaling in Europe	Policy report
Pauliuk et al.	2021	Global scenarios of resource and emission savings from material efficiency in residential buildings and cars	Scientific journal
Pristerà et al.	2024	Taxonomy of design for deconstruction options to enable circular economy in buildings	Scientific journal
Scrivener et al.	2018	Calcined clay limestone cements (LC3)	Scientific journal
Shanks et al.	2019	How much cement can we do without? Lessons from cement material flows in the UK	Scientific journal
Silva et al.	2017	Availability and processing of recycled aggregates within the construction and demolition supply chain: A review	Scientific journal
UN Environment et al.	2018	Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry	Scientific journal
Viczek et al.	2020	Determination of the material-recyclable share of SRF during co-processing in the cement industry	Scientific journal
Zhang et al.	2019	A review of life cycle assessment of recycled aggregate concrete	Scientific journal
Zhang et al.	2019	Eco-efficiency assessment of technological innovations in high-grade concrete recycling	Scientific journal
Zhang et al.,	2020	Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands	Scientific journal
Zhang et al.	2022	An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe	Scientific journal
Zhutovsky & Shishkin	2021	Recycling of hydrated Portland cement paste into new clinker	Scientific journal
Zibell et al.	2022	Impacts of Circular Economy on EU climate policies - mitigation and adaptation	Policy report
Zunoni	2023	A two-fold strategy towards low-carbon concrete	Scientific journal

Source: JRC elaboration

The data from selected sources was analysed using a qualitative method based on a deductive coding procedure (Fereday & Muir-Cochrane, 2006). This method entails performing a thematic clustering of insights derived from diverse written sources, guided by pre-existing conceptual categories relevant for the analysis. In particular, information on cement and concrete circularity levers from selected sources was merged and integrated into a list of levers structured according the classification provided in section 2.1. By doing so, the list that was obtained by including all references reported in was reduced to a preliminary list of 12 levers. Demand-based levers such as reduction of living space were omitted due to their wider socio-economic implications and reliance of policy makers on the cooperation of citizens. The reason is that a limitation of consumption could lead to controversial policies such as increasing prices for living space or quotas, if the reduction is enforced against the preference of citizens. It is unlikely to assume that social actors would reduce their demand for living space voluntarily.

Step 3: Levers validation

The preliminary list of levers based solely on the analysis of literature was consequently validated with industry experts from CEMBUREAU, BIBM as well as with academics and colleagues from the Joint Research Centre of the European Commission. Following a conversational interview approach (Patton, 2002), a video conference was organised with the abovementioned experts. In this consultation, various levers were discarded, complemented with more detail and/or merged in view of feasibility considerations within the industry context. This resulted in an updated list of 11 levers. This step also enabled to collect initial information on a possible quantification of the effects of the levers.

Step 4: Levers quantification

After validation, the fourth step entailed the quantification of the effect of the levers. This was done by retrieving quantitative data available from the original source documents and the supplementary material provided by a subset of documents form the full list of selected literature presented in . In the process, the list of levers had to be updated, checked by industry players again, adding, eliminating, or subtracting elements, also depending on bottom-up modelling possibilities and constraints. This resulted in the final list of levers, complemented with categorisation and quantification, as presented in the overview provided in **Table 1**. In the following section, each lever is explained in greater detail.

2.1 Description of circularity levers and implementation in the modelling

The following paragraphs describe both the levers as well as the reasoning for their quantification in detail. At this points it is worth recalling that clinker is the environmental hotspot of cement production, which is why the CE levers are applied in a way that the use of clinker in cement and concrete is minimised. It is important to note that the levers have been implemented individually, grouped by CE cluster as well as an aggregated maximum, to isolate the effects of the individual levers, while analysing their interconnection. In a final step, the combination of all levers in the ambitious circularity scenario is explained.

1. Clinker raw material substitution

During the co-processing of waste-derived fuels for clinker production, a part of the burned ashes is directly taken up by the clinker, and thus replacing part of the raw materials (Viczek et al., 2020). This share is currently not considered as recycled content by EU legislation, as it is coming from a different life cycle (Enengel et al., 2023). However, the direct uptake into raw material (as opposed to fly ash ashes added from municipal waste incineration (Marieta et al., 2023)) justifies the inclusion of this lever and has been advocated for by industry (Alarcón et al., 2022; Viczek et al., 2020). The effect of the ashes on the composition of the clinker depends significantly on the inputs. The most types of wastes used as fuel are refuse derived fuel, animal meal, sewage sludge, old rubber tyres and wood waste (Alarcón et al., 2022). It is therefore necessary to identify the exact composition of the waste and ensure the compatibility of the resulting ashes' chemical composition with the local raw material mix (Clavier et al., 2020). It needs to be underlined that not all of the ashes which is created during the combustion process is directly taken up by the clinker (Viczek et al., 2020). In terms of contribution of heavy metals, RDF particularly contributes to the content of copper, nickel, lead, antimony and chromium (Enengel et al., 2023). Moreover, it was found that the optimal share taken up by the clinker was about 5% of the raw meal mixture from a composition point of view, while this is also depending on the availability from the ashes. Based on the calculations made by García-Gutiérrez et al. (2023) serving as a foundation of the kiln energy modelling, the produced ashes per MJ of combustion is too low to enable a take-up rate of 5%.

While the cement industry is advocating for considering co-processing itself as an R-strategy, reducing landfill, this perspective is not necessarily shared by scholars, as it requires increased supply of waste streams and, in particular, biomass (Georgiades et al., 2023; Mission Possible Partnership, 2023). Firstly, this would increase the demand for waste, and in particular waste with high caloric value, such as plastics, for which higher value options such as recycling are preferred and which should in general be reduced. Secondly, the creation of these waste streams is again connected to environmental impacts and in the case of biomass, to land use, indicating that the cement industry would compete for these resources in a constrained market (A. Müller et al., 2024). Finally, the effect of inter-country shipment of waste from landfills to cement plants is yet to be assessed. So while there are gains to make in the cement industry with regards to CO_2 reductions by diversifying energy sources, these do not necessarily translate in CE R-strategies, and the systemic environmental impacts remain uncertain.

Table A 3. Modelling of lever on clinker raw material substitution

Year	**Status quo**	**2050**
Value	0-2.5%	Up to 5%
Type	Supply side	
Circular economy cluster	Reduce	
Modelling interpretation	• Using the ashes of co-processing as input for clinker production, limited by the availability of the ashes resulting per MJ of combustion • Material replaced is calcareous marl and related calcination emissions are omitted • System boundaries are extended and the alternative scenario of the ashes going to landfill is subtracted from the impact of the clinker production	

Assumptions on the elaboration of the data taken from literature	• The ashes produced by the respective heat mix in the kiln is calculated based on Garcia-Gutierrez et al. (2023) and connected to the heat needed per kg of clinker production. For 2020, 0% is estimated as to present the effect of considering it as a viable lever. • The heat per kg of clinker is going to reduce from 3.87 MJ/kg to 3.02 MJ/kg due to technical efficiency improvements (Georgiades et al., 2023), resulting in a max of 2.5% of ashes available for raw meal in 2050. Therefore, the technical maximum of 5% are not achieved (Viczek et al., 2020). • This offers the option of replacing the remaining 2.5% by recycled cement fines (Lever 6), of which a higher composition share is tolerated, while maintaining the functional properties of the material
Limits and improvements	• The composition of clinker needs to be analysed case by case to ensure suitable material properties (Clavier et al., 2020; Viczek et al., 2020) • The ashes from combustion is usually not fully integrated into the clinker, potentially leading to an overestimation (Viczek et al., 2020) • Though industry and several scholars consider the recovery of ashes as a form of material recovery, it is not accepted as such by European Union regulation (Enengel et al., 2023)

Source: JRC elaboration

2. Cement substitution with alternative binders

Besides substituting parts of the cement or its raw materials with supplementary cementitious materials, there is also significant research on alternative types of cement (Favier et al., 2018; IEA and WBCSD, 2018; Miller & Myers, 2020). These cements do not directly reduce material flows themselves, but, depending on their composition, decrease the process-related CO_2-emissions significantly, due to reduced calcination and heat requirements (Miller & Myers, 2020). There are several types of alternative binders: reactive belite portland cement (RBPC), belite ye'elimite ferrite (BYF) cement, carbonatable calcium silicate cement (CCSC), magnesium oxide cement (MOM), and calcium sulfoaluminate-belite (C$AB) cement. In recent years, both the importance of biocements and geopolymers has also increased but these materials have yet to penetrate the market (Nilsson & Verschaeve, 2023) However, Favier et al. (2018) deem calcium sulphoaluminate cement and carbonatable calcium silicate cement to be most likely to be used at industrial scale by 2050.

Given the overall similar inputs to the current cement production, limited retrofitting of plants would be needed, which implies that additional costs for switching production would be manageable (Gartner & Sui, 2018). Moreover, for calcium sulphoaluminate cement, the industry might build on the experience in China, where this type of cement has been used for over 40 years already at industrial scale (Favier et al., 2018). However, due to its aluminate content there is competition with other sectors, leading to a potential price increase for parts of the raw materials and thus limiting its market share (IEA and WBCSD, 2018). For carbonatable calcium silicate cements, there are limitations with regards to applications on site. First, as the cement requires CO_2 rather than water for hardening, it is more suitable for pre-cast concrete. Secondly, the reduced alkalinity of the materials does not protect steel reinforcement from corrosion, leading to an overall limited market penetration (Favier et al., 2018). Finally, the use of both of these types of alternative binders strongly depends on the local availability of the raw materials (Gartner & Sui, 2018), which is a similar issue like the one encountered for the use of different supplementary cementitious materials.

Table A 4. Modelling of lever on cement substitution with alternative binders

Year	**Status quo**	**2050**
Value	0%	Up to 10%
Type	Demand side	
Circular economy cluster	Reduce	
Modelling interpretation	• Production of alternative binders and the respective calcination emissions are modelled • Due to the material properties, the alternative binders are modelled to replace CEM I and CEM II	
Assumptions on the elaboration of the data taken from literature	• In line with Favier et al. (2018) and Nilsson & Verschaeve (2023), up to 10% of cement can in the future be replaced by alternative binders. • The most promising ones are calcium sulphoaluminate cement and carbonatable calcium silicate cement (Favier et al., 2018; Gartner & Sui, 2018), modelled according to Miller & Myers (2020). • The two types of alternative binders are assumed to represent 50% of the share each and replace CEM I and CEM II in equal parts, due to their similar properties and use cases. • Though the alternative binders are at times referred to as clinkers, it is assumed that no additional supplementary cementitious materials or inputs are added to them, before mixing them into concrete. • Given the similarity of raw material and manufacturing equipment needed, retrofitting costs are omitted and equal costs of raw materials assumed. • The CO_2 used for hardening the carbonatable calcium silicate cement in the concrete is not modelled and could therefore lead to an underestimation. • In terms of use, it is expected that 40% of alternative binders will be ready mixed concrete, 50% pre-cast concrete (given the higher control of external factors) and 10% for mortar.	
Limits and improvements	• There might be an underestimation of the costs for raw material • Strongly depending on local material availability (Gartner & Sui, 2018)	

	- Acceptability by the market was not assessed beyond literature (IEA and WBCSD, 2018; UN Environment et al., 2018)

Source: JRC elaboration

3. Clinker substitution in cement by supplementary cementitious material

The current share of clinker in cement in Europe is about 77% (CEMBUREAU, 2024b; Material Economics, 2018). However, this share can potentially be reduced to below 50%, from a technical perspective (Favier et al., 2018; Habert et al., 2020; Nilsson & Verschaeve, 2023), and to about 60% from a market perspective (CEMBUREAU, 2020). The clinker will be substituted by supplementary cementitious material, which is currently composed of industry by-products such as blast furnace slag, fly ash, foundry sand or silica fume, but also raw materials like limestone, natural pozzolana, gypsum and calcined clay (IEA and WBCSD, 2018). Several industry players and a few scholars advocate for the increased use of by-products from carbon intensive industries such as steel or municipal waste incineration, which have been taken up well by the market and the relevant cement standards (Olsson et al., 2023; Zibell et al., 2022). However, other scholars have called for caution, given the phase out of fossil fuels and changes in steel production, constraining these by-products in the future (Król et al., 2020; UN Environment et al., 2018). Nilsson et al (2020) project that by 2050 the traditional SCMs from by-products will be reduced to only 10% of the SCM market, and replaced by virgin SCMs.

Indeed, scholars and increasingly industry actors see the importance of diversifying the SCMs, and in particular driving forward the use of calcined clay or limestone (GCCA, 2022; Mission Possible Partnership, 2023; Scrivener et al., 2018; Zunino, 2023). Both of these materials are ubiquitously available at similar prices, though potentially not in the same region as the current cement kilns are located (Nilsson et al., 2020). While certain SCMs lower the compressive strength of concrete or increase the hardening time, LC3, based on calcined clay, has shown to have a performance similar to CEM I and CEM II, and longer service lives in reinforced concrete (Pillai et al., 2019; Zunino, 2023). Besides the uptake of these SCMs into cement standards, it is essential to further educate engineers and architects about the existence of these materials and their functional properties, thus including the whole construction supply chain (Dewald & Achternbosch, 2016; Favier et al., 2018; Habert et al., 2020). While LC3 has sparked increasing interest in the academic community (Barbhuiya et al., 2023; Mañosa et al., 2024), a special feature of it is that it has frequently been applied out of Europe, where the population increase will lead to higher concrete demand (Scrivener et al., 2018).

Table A 5. Modelling lever on clinker substitution by supplementary cementitious material

Year	**Status quo**	**2050**
Value	23%	Up to 43%
Type	Demand side	
Circular economy cluster	Reduce	

Modelling interpretation	• Production of low carbon cement with calcined clay are modelled • Grounded blast furnace slag is expected to play less of a role in the future • Clinker rate will be reduced in accordance with cement and building standards
Assumptions on the elaboration of the data taken from literature	• CEM I and CEM II are each reduced by half of the projected 15% market rate of low carbon cement with calcined clay (Favier et al., 2018; IEA and WBCSD, 2018; Mission Possible Partnership, 2023) • Both CEM II and generic cement increase their level of SCMs by 74% compared to the status quo composition (Favier et al., 2018; Material Economics, 2018; Nilsson et al., 2020) • The SCMs are expected to change in their composition, as many of them are a by-product of fossil-based energy production, which is expected to phase out. Thus, the share of grounded blast furnace slag of steel production is modelled to drop by 50%, particularly affecting the production of CEM III and certain types of CEM II (IEA and WBCSD, 2018; UN Environment et al., 2018). This is in contrast to other studies (Olsson et al., 2023; Zibell et al., 2022), which have proposed an increase of these types of SCMs. • The combined effect of these measures achieves a clinker rate of 57%, below the targeted 60% of CEMBUREAU (2024)
Limits and improvements	• SCM availability depends on speed of decarbonisation of related industries such as steel (UN Environment et al., 2018) • SCM use is strongly affected by industry uptake and supply chain collaboration (Dewald & Achternbosch, 2016; Favier et al., 2018; Habert et al., 2020) • Composition of the SCM ecoinvent process is not adapted for the future composition. However, it only makes up a minority of the SCMs modelled.

Source: JRC elaboration

4. Substitution of concrete with timber

Another substitution of concrete, which is strongly depending on regional availability of the raw materials, is the use of timber. In the past, it has been advocated as a promising material to lower the CO2 emission profile of construction in general, but researchers underline the applicability of this claim is conditioned by its aforementioned availability (Pauliuk et al., 2021). Especially in Northern European countries, where forestry contributes largely to the first sector and has been managed sustainably for decades, construction with timber is seen as a viable alternative (Hansen et al., 2024). The most common forms in which timber is used are cross laminated timber and solid glued timber, both employed as structural elements of buildings (Andersen et al., 2022b; Brandner et al., 2016). However, there are limitations to the application of these materials from a structural perspective concerning building height. Therefore, they are mainly used in single-family houses, office buildings and multifamily houses (Hansen et al., 2024). In terms of lifetime of buildings, these are not expected to vary significantly from concrete buildings, as demolition rarely occurs due to the degradation of the main structure, but rather due to changes in the use of the area (Material Economics, 2018).

Both of these materials have lower climate change impacts than comparable amounts of concrete. However, other impact categories such as land and water use, as well as toxicity due to the glue are generally higher than for concrete. With regard to land use, Andersen et al. (2022) underlines, that the main reason for deforestation is not projected to be the use of timber in the construction of buildings, but in the energy used during their operation. Moreover, Hansen et al. (2024) found, that depending on the building type (e.g. office buildings and single-family houses), building with timber is not necessarily favourable even from a climate change perspective. This also relates to the fact that with an increase in timber, other materials such as steel also tend to increase to ensure the structural integrity. Therefore, the selection of steel suppliers (European or from third countries) greatly influences the level of embedded emissions of the materials.

Table A 6. Modelling of lever focused on substitution of concrete with timber

Year	**Status quo**	**2050**
Value	Current use	Up to 10% of concrete for buildings
Type	Demand side	
Circular economy cluster	Reduce	
Modelling interpretation	• Demand for concrete is reduced and replaced with solid glued timber and cross laminated timber • The system is extended by the timber life cycle from cradle to grave	
Assumptions on the elaboration of the data taken from literature	• Given about 22% of aggregates and cement goes to plasters and mortars, and not concrete, and the substitution is only intended for buildings, making up 50% of the materials used, the overall demand is decreased by 3.7% for cement and 4.05% for aggregates (Material Economics, 2019) • The mass of timber required to substitute structural concrete is based on Andersen et al. (2022), specifying that 690 kg of timber replace 1410 kg of concrete. This results in 0.49 kg of timber per 1kg of concrete reduced. • The modelling of the wood life cycle is based on Caro et al. (2024) for the end of life, with energy use according to the GECO 2023 report, and Ecoinvent 3.9.1 processes for the production of solid glued timber and cross laminated timber. These two types of timber make up 50% of the replaced material each.	

	- The percentage of wood going to demolition (19%) is based on the MFA of Damgaard et al. (2022)
Limits and improvements	- Construction with timber vs. concrete involves differing ways of designing a building, which lead to highly varying substitution rates (Andersen et al., 2022b) - In certain instances, timber construction requires additional steel which is currently not modelled (Hansen et al., 2024) - Availability is limited to northern European countries and many impacts related to land use and biodiversity still insufficiently researched (Agora Industrie & SYSTEMIQ, 2023; Hansen et al., 2024)

Source: JRC elaboration

5. Reduce cement in ready-mixed concrete

Depending on the required strength class and exposure class of concrete, different amounts of cement are required. These requirements are specified in the cement and building standards, developed both on national and European level (C. Müller, 2023). Due to safety concerns, the use of cement ready-mixed concrete is usually up to 20% higher than the one required by these standards, leading to inefficient amounts of cement in concrete (Material Economics, 2019). While structural elements will continue to require about 300 kg of cement per m3 of concrete, Favier et al. (2018) argue that in buildings, this average can be brought down to 285 kg/m3, with some types of cement as low as 150 kg/m3 (Habert et al., 2020). Part of this cement can be replaced by fillers such as finely grinded limestone, but this is not industry practice at the moment. Moreover, this optimisation requires high quality of aggregates, which strongly depends on local availability (Favier et al., 2018; Material Economics, 2019). Therefore, a more conservative reduction of cement without the addition use of limestone and ad-mixtures is assumed, where the density of the concrete is reduced.

Table A 7. Modelling of lever focused on reduction of cement in ready mixed concrete

Year	**Status quo**	**2050**
Value	0%	Up to 5% reduction in ready mixed concrete
Type	Supply side	
Circular economy cluster	Reduction	
Modelling interpretation	- Demand for cement is reduced in ready mixed concrete by adhering more strictly to building standards - Demand for aggregates remains unaffected	
Assumptions on the elaboration of the data taken from literature	- Ready-mixed concrete makes up 35% of concrete used and cement can be reduced by 5%, from 300 kg/m3 to 285 kg/m3, resulting in an overall reduction of 1.75% (Favier et al., 2018)	

	- The mass of aggregates remains unaffected, while the density of the concrete is reduced.
Limits and improvements	- Builders tend to use excessive amounts of cement, superseding the structural requirements specified in building standards (C. Müller, 2023). However, it is difficult to encourage a reduction of the cement, due to the engineering offices resorting to standard values for adhering to standards (Agora Industry, 2022; Favier et al., 2018; Material Economics, 2018). Policy instruments such as eco-design measures can support such shifts.

Source: JRC elaboration

6. Reduce concrete in buildings

While amount of concrete in civil engineering infrastructure is expected to be optimised, this is not necessarily the case for buildings, where engineering offices tend to resort to default values (Favier et al., 2018). The reason for this inefficient use of concrete are safety concern on the one hand, and the low price of concrete, when compared to the overall construction project costs, on the other (Material Economics, 2018). Furthermore, structural building elements tend to be overspecified, carrying only 50% of their maximum loadable weight. The use of 3D printing, more pre-fabricated elements, post-tensioning and less construction waste are proposed to achieve this reduction (Material Economics, 2019). However, it has also been mentioned by the industry that these types of savings could be offset by the increased concrete demand for infrastructure resilient against climate change, mass transportation systems and renewable energy use (CEMBUREAU, 2020).

Table A 8. Modelling of lever focused on reduction of concrete in buildings

Year	**Status quo**	**2050**
Value	0%	Up to 40% in buildings
Type	Demand side	
Circular economy cluster	Recovery	
Modelling interpretation	- Demand for concrete is reduced only in buildings - Less demand for cement and aggregates	
Assumptions on the elaboration of the data taken from literature	- Given about 22% of aggregates and cement goes to plasters and mortars, and not concrete, and the substitution is only intended for buildings, making up 50% of the materials used, the overall demand is decreased by 14.8% for cement and 16.2% for aggregates (Material Economics, 2019). The discrepancy in demand reduction is due to the different composition of ready-mixed and precast concrete and mortar, the latter of which is excluded from the lever. - Lever does not apply to civil infrastructure and maintenance, as it is assumed that material use is already optimised in these categories (Favier et al., 2018).	

Limits and improvements	• Builders tend to use excessive amounts of concrete, superseding the structural requirements specified in building standards (C. Müller, 2023). However, it is difficult to encourage a reduction of concrete, due to prevailing safety concerns and the low material costs, in comparison to the total construction costs (Favier et al., 2018; Material Economics, 2018, 2019). Policy instruments such as eco-design measures can support such shifts. • In some studies (e.g. CEMBUREAU (2020)), the reduction of the use of concrete in buildings is not considered as a lever, as it might be offset by the additional concrete necessary to repair the damage of natural disasters caused by climate change. However, additional concrete demand due to natural causes and the resulting higher 'natural' demolition, are not taken into account.

Source: JRC elaboration

7. Extend lifetime by renovation and reuse of structural parts in situ

While buildings are currently built with a projected lifetime of 60-100 years, statistical data have shown that their actual lifetime can be considerably longer with adequate maintenance and renovation (S. P. Deetman, 2021; Material Economics, 2018). The demolition of buildings is thus not much owed to material deterioration, but more often to change of use of the area, energy use optimisation of new buildings, high costs of renovation or different preferences of house owners (Damgaard et al., 2022; Material Economics, 2018). Being conscious of the significant environmental benefits of extending the lifetime of buildings, by simply not demolishing them, or by retrofitting them, can thus reduce the demand for construction (Damgaard et al., 2022). The extension of lifetime has been applied as a lever in both material flow analyses and input output analyses (Donati et al., 2020; Pauliuk et al., 2021). In both cases, the demand of service provided by the material (in this case m2 of concrete in the EU) were identified and the required material inflow, stock and outflow determined to satisfy this demand, in correspondence with the average age of buildings. The lifetime extension is for the building structures, typically reported per m2 of occupied area (or total floor area). As building types differ in material intensities per m^2, there is usually a differentiation between residential buildings, expected to constitute 62% of the demanded m^2 in 2050 and non-residential buildings, accounting for the remaining 38% (Damgaard et al., 2022). In line with propositions by Damgaard et al. (2022) and Deetman (2021), the age of residential buildings is extended by 20 years and the age of non-residential buildings by 10 years. These values stem from the upper bound of lifetime of buildings, with Eastern European buildings having the longest average lifetime (Damgaard et al. 2022).

Since previous models mostly applied lifetime extension to new buildings only, this would not yield any effects to the end of life in the current analysis, because they would yield effects after 2050. However, it was considered important to apply the lifetime extension to the existing building stock as well, given the large potential of material savings and available policy instruments to increase renovation (Damgaard et al., 2022; Material Economics, 2018; Thung et al., 2024). To model the effects at the end of life, the volume of demolition decreases as well, though to a lesser extent. This is due to the fact that demolition is commonly modelled according to the Weibull distribution, which spreads the likelihood of demolition across several years, taking into account the age cohorts of the stock (S. Deetman et al., 2020; Lotz et al., 2024).

Table A 9. Modelling of lever focused on building lifetime extension

Year	**Status quo**	**2050**
Value	Ca. 87 years	Ca. 103 years
Type	Demand side	
Circular economy cluster	Reuse	
Modelling interpretation	• Demand for concrete is reduced • Demolition coefficient decreases by applying the Weibull distribution to the absolute demand decrease for concrete in buildings	
Assumptions on the elaboration of the data taken from literature	• Lifetimes of residential buildings are currently at 100 years and estimated to be extendable to 120 years on average, while for non-residential buildings, the current 65 years are extended to 75 in line with Damgaard et al. (2022), Deetman (2021) and Marinova et al. (2020) • The lifetime increase is estimated by the difference of the total concrete demand necessary to satisfy the surface area required by the population (demand = construction inflow – demolition outflow + stock = stock change + stock) divided by the current lifetime (86.57 years) and the total concrete demand, divided by the extended lifetime (102.74). This yields a 16% demand reduction, which is, for simplification, implemented at the same time as a lifetime extension. • The demolition rate is adapted by the demand reduction, though the effect is delayed by 16 years, i.e. the difference between the old and new lifetime. To identify the effects of the delay, the age of the material stock is determined from the Damgaard et al. (2023) study and the Weibull distributions shifted forward on the x-axis by 16 years. This results in 19,3% less demolition of buildings (assumed to make up 50% of demolition, in line with the share of construction), leading to 2.6% lower demolition rates (from 27.8 % to 25.2%) with respect to construction. • Because concrete is not as prevalent in renovation as other materials, additional use of concrete for maintenance services or renovation is omitted. • In contrast to other publications (Donati et al., 2020; Pauliuk et al., 2021), the lifetime extension is applied to existing and future buildings, and the lever is only starting to have an effect in 2050, with direct effect also on the end of life.	

Limits and improvements	• Stock models differ largely resulting in uncertainties of size of the actual building stocks, their age and related in and outflows (Deng et al., 2023). The distribution of demolition parameters should be calibrated as close as possible to actual demolition data, which is available for 2020, but uncertain for the future. • The lifetime of buildings in material flow models is often underestimated, when compared with statistical data, which could lead to an underestimation of the lifetime extension (S. P. Deetman, 2021). While for this study comparatively large lifetime extensions are assumed, they could still be too low. • The effects are modelled in a way that attribute a shock to both demand and end of life in the same year. The way of implementation here simply represents the total potential of the lever, while its implementation is most probably more gradual. • Lifetime might be affected by advancements in design with lower operating costs, use change and change of standards and legislation (Olsson et al., 2023). • The lever is agnostic in how the lifetime extension is to be achieved, i.e. if it is a repurposing of a building, or if merely the concrete structure is reused. It only stipulates that no additional concrete material flows are needed for e.g. renovation, given concrete is typically not used as much as e.g. ceramics or glass (Damgaard et al., 2022). Including additional materials used for renovation (besides concrete) could provide a more complete picture of environmental impacts. This would require additional data on the share of lifetime extension due to renovation vs. repurposing, which is currently not available.

Source: JRC elaboration

8. Reuse of pre-cast elements

The reuse of pre-cast elements both on site and at other sites to date is minimal, and mostly at pilot stage (Knoth et al., 2022; Pristerà et al., 2024). Recycling of concrete to recycled aggregates (referred to below) is at times also considered reuse by scholars (Nußholz et al., 2020). In this study however, it is only considered as such, if concrete is directly reused in its present form, with a similar structural function. The review by Pristerà et al. (2024) showed that the different elements range from structural concrete, to staircases, panels and roof tiles, each with their own reuse potential. It is at times also difficult to distinguish between reuse and lifetime extension, given that at times structural or foundational concrete is integrated into the new building (Devènes et al., 2024). As these cases are partially covered in the lever on lifetime extension, this lever focuses on reuse at different sites only. As concrete elements cast on site are usually not constructed in a modular way, only pre-cast elements are considered.

A pre-requisite for reuse is selective demolition, which assesses both the quality and longterm integrity of the reused pieces (Devènes et al., 2024). This guarantees that the structural properties of the reused product will fulfil the structural requirements of its intended new purpose. Industry actors have pointed out that the general trust in second-hand structural concrete is considered low, as no party would like to carry the risk in case of material failure. Other barriers are the lack of storage, diverging timelines of demolition and construction, limited market interest as well as a poor legal framework with corresponding standards (Knoth et al., 2022). Also, in this case, the collaboration and communication throughout the value chain, but especially between construction procurement and demolition services is paramount. Besides the legal and actor-specific changes required, design for deconstruction is a more technical paradigm that is meant to enable reuse and is slowly finding its way into architectural and engineering bureaus (Kim & Kim, 2023).

Table A 10. Modelling of lever focused on reuse of pre-cast elements

Year	**Status quo**	**2050**
Value	0%	Between 15-20%
Type	Demand side	
Circular economy cluster	Reuse	
Modelling interpretation	• At the EoL, concrete is reused after selective demolition • Pre-cast concrete is expected to replace virgin concrete	
Assumptions on the elaboration of the data taken from literature	• Only material from selective demolition is reused • Though the exact percentage of selective demolition is currently not available, it is expected that at least 95% of demolition will be selective in 2050 • The amount of reused material is reduced from the material available for recycling • Pre-cast expected to make up 18% of demolished material, which is likely to be an overestimation, given that its share has been lower in the past decades, when the demolished buildings were built. • It is expected that 17,5% of all pre-cast will be reused, based on an average of the values in Material Economics (2018) and Pristerà et al. (2024) • The process replaced by reused concrete is the production of virgin precast concrete • It is assumed that there is no quality loss of the reused material over its second lifetime (Pristerà et al., 2024) and that its suitability for reuse has been assessed, in line with guidelines by Devènes et al. (2024) • The processes and costs involved in reuse are modelled in accordance with Caro et al. (2024)	

Limits and improvements	• Limited proof of concept and poor industry uptake • Limited communication throughout value chain and especially between manufacturers and project developers leads, amongst other reasons, to poor industry uptake (Knoth et al., 2022; Nußholz et al., 2019) • Problem of safety insurance and transport of precast elements • Actual reuse potential is deemed significantly higher, but involves extensive preliminary assessment. Moreover, reuse could also be extended to non-precast concrete, though limiting the transport of the concrete elements (Devènes et al., 2024)

Source: JRC elaboration

9. Recycle concrete to clinker raw material

Concrete fines from construction and demolition waste can be used to replace a certain percentage of calcareous marl or, to a lesser degree, limestone (Diliberto et al., 2017; Krour et al., 2020). Depending on the exact composition of the fines, the substitution could reach up to 25%, though, again, this would have to be assessed in laboratory tests, where the raw materials, recycled fines, and potentially the ashes from the alternative fuels are combined. Therefore, a more conservative share below 10% is generally recommended (Krour et al., 2020). The processes to obtain the fines in the necessary size and quality are still at a low stage (TRL 6-7), with strong variations across countries (Zhang et al., 2022). One of the most promising examples are a combination of the Heating-Air classification System in connection with the Advanced Dry Recovery (Gebremariam et al., 2020; Moreno-Juez et al., 2020), which create ultrafine concrete fines (<0.25 mm), separating the sand from the cement paste. These fines can be used both as raw material for clinker or as substitute of cement in concrete, as will be described below. However, the capacity of the HAS is still low, at 3 t/h, and it is powered by diesel energy. Therefore, an increase of capacity as well as potential switch of energy source to e.g. biofuel or electricity is proposed (Gebremariam et al., 2020).

The market of this secondary material is still small due to both capacity and investment constraints. Therefore, though technically a significant share of the raw material could be replaced by concrete fines, its limited availability and strong regional variation of supply have, to date, prevented wider market uptake (Zhang et al., 2022). From a material loop perspective, one could argue that concrete is already recycled at high rates to recycled aggregates and question the potential improvements of processes like ADR and HAS. Yet, the fact that these ultrafine fractions can replace either the raw material of clinker or cement itself, making up the most energy intensive inputs of concrete, makes the solution much more promising from an environmental perspective (Diliberto et al., 2017; Zhutovsky & Shishkin, 2021).

Table A 11. Modelling of lever on recycling concrete to clinker raw material

Year	**Status quo**	**2050**
Value	0%	Up to 20%
Type	Supply side	

Circular economy cluster	Recover
Modelling interpretation	- At the end of life the HAS process is implemented producing fines that can be used as cement or clinker raw material replacement - Material replaced is calcareous marl and related calcination emissions are omitted
Assumptions on the elaboration of the data taken from literature	- The novel technology (TRL 6-7) Heating-Air classification System is applied in connection with the Advanced Dry Recovery in line with Gebremariam et al. (2020), Moreno-Juez et al. (2020) and Zhang et al., 2019) - The above value of 20% of the market demand for cement is only a technical reference, which has not directly been modelled. Instead, the maximum availability has been estimated through the ADR and HAS, with their respective capacity limitations. - It is assumed that 50% of all concrete coming from the selective demolition stream (50% of total demolition in the Baseline, 95% in Ambitious Circularity) is going ADR, of which then 40% is entering HAS, resulting in clinker raw material substitute making up 20% of the input material. - The substitutability rate is set at 0.652 of the replaced material based on Krour et al. (2020), with an assumed 15% that can be incorporated into the total raw material mix, of which 23% is calcareous marl.
Limits and improvements	- Up to 20% replacement is claimed though technically only 10-15% are recommended (Diliberto et al., 2017; Krour et al., 2020; Zhutovsky & Shishkin, 2021) - Market availability is limited, given that demolition outflows are modelled as 27% of the inflows, of which only a minor percentage is treated by ADR and HAS - The composition of clinker needs to be analysed case by case to ensure suitable material properties, especially when combined with ashes from co-processing (Clavier et al., 2020; Viczek et al., 2020)

Source: JRC elaboration

10. Recycle concrete to cement substitution

The supplementary cementitious materials can also stem from concrete itself, closing the loop of the cement and concrete life cycle. Construction and demolition waste can replace a certain percentage of cement in concrete, with an estimated maximum of 10% and an optimum of 5% (Moreno-Juez et al., 2020). The processes to obtain the fines in the necessary size and quality are still at a low stage (TRL 6-7), with strong variations across countries (Zhang et al., 2022). One of the most promising examples are a combination of the Heating-Air classification System in connection with the Advanced Dry Recovery as previously described (Gebremariam et al., 2020; Moreno-Juez et al., 2020). Indeed, the recycled cement fines produced can also be used to replace cement directly, rather than the aforementioned raw material for clinker. Though the same technology is used, the levers were applied separately to showcase the difference in result when substituting different materials.

Table A 12. Modelling of lever focused on recycling concrete for cement substitution

Year	**Status quo**	**2050**
Value	0%	Up to 10%
Type	Supply side	
Circular economy cluster	Recover	
Modelling interpretation	• At the end of life, the HAS process is implemented producing fines that can be used as cement or clinker raw material replacement • Material replaced is CEM undef with a clinker factor of 57%	
Assumptions on the elaboration of the data taken from literature	• The novel technology (TRL 6-7) Heating-Air classification System is applied in connection with the Advanced Dry Recovery in line with Gebremariam et al. (2020), Moreno-Juez et al. (2020) and Zhang et al., 2019) • The above value of 10% of the market demand for cement is only a technical reference, which has not directly been modelled. Instead, the maximum availability has been estimated through the ADR and HAS, with their respective capacity limitations. • It is assumed that 50% of all concrete coming from the selective demolition stream (50% of total demolition in the Baseline, 95% in Ambitious Circularity) is going ADR, of which then 40% is entering HAS, resulting in cement substitute making up 20% of the input material. • The substitutability rate is assumed at 0.71 of the replaced material based on Fořt & Černý (2020) and contact with industry partners	
Limits and improvements	• Up to 10% replacement is claimed though technically only 5% are recommended (Moreno-Juez et al., 2020), and market availability is limited • Market availability is limited, given that demolition outflows are modelled as 27% of the inflows, of which less than half is treated by ADR and HAS • The composition of clinker needs to be analysed case by case to ensure suitable material properties, especially when combined with ashes from co-processing (Clavier et al., 2020; Viczek et al., 2020)	

Source: JRC elaboration

11. Recycle concrete to recycled aggregates

The recycling of concrete is one of the levers with the highest application rate, though practices vary widely across EU countries (Pacheco et al., 2023). For obtaining high quality recyclate, in this case, recycled aggregate concrete, selective demolition is a pre-requisite. The wet processing is the one mostly used by industry (Etxeberria et al., 2022), while the ADR and HAS previously discussed also create coarse and fine recycled aggregate fractions (Zhang, Hu, Dong, Gebremariam, Miranda-Xicotencatl, et al., 2019). Usually, coarse and fine recycled aggregates have different qualities, with coarse fractions showing higher substitutability rates than fine fractions (Bayram & Greiff, 2023; Le & Bui, 2020). The reason for this is that the fine fraction contains a higher percentage of mortar, which has less structural integrity than sand or gravel (Pacheco et al., 2023). Moreover, a 100% substitutability of natural aggregates with coarse recycled aggregates is still not recommended for reasons of mechanical properties (Colangelo et al., 2021), but also not possible, as the current aggregates only make up 8% of the total aggregates used (Aggregates Europe, 2022; Pacheco et al., 2023). This stems from the fact that the demolition rate of concrete is currently only at about 11% of the construction rate, and while it is expected to increase in the future, it will not allow for a substantially higher substitution of virgin material (Damgaard et al., 2022; S. Deetman et al., 2020). However, it is expected that a redirection of current backfilling and landfilling practices can increase the share of produced recycled aggregates nevertheless. While landfilling is to be minimised through both economic incentives and landfill bans or limitations (Luciano et al., 2022), de-facto backfilling is currently still counted as recycling in some member states, and can thus be reduced further (Cristóbal García et al., 2024; Moschen-Schimek et al., 2023).

However, except in places of raw material scarcity, there are still significant barriers to the market uptake of recycled concrete aggregates, such as transport distance, client perception, scepticism by engineering offices and a lack of standardisation of secondary products (Silva et al., 2017). Therefore, the communication between construction companies, demolition companies and cement and concrete producers are critical, to ensure trust in the novel raw material (Luciano et al., 2022). Furthermore, policy incentives such as green public procurement or end of waste criteria, as they are currently being developed, are expected to increase the diffusion of these materials significantly (Pacheco et al., 2023; Silva et al., 2017). While the further increase of recycling can indeed create certain environmental benefits, it is important to underline that the environmental impact reduction from recycling concrete back to clinker raw material or cement replacement is far higher (Caro et al., 2024; Le & Bui, 2020; Moreno-Juez et al., 2020).

Table A 13. Modelling of lever focused on recycling concrete to recycled aggregates

Year	Status quo	2050
Value	77% for recycling	Up to 95% for recycling
Type	Supply side	
Circular economy cluster	Recover	
Modelling interpretation	• The share of material undergoing increases at the expense of landfill and backfilling	

	• The recycled material is expected to be sent to the wet recycling process, producing washed recycled concrete aggregates
Assumptions on the elaboration of the data taken from literature	• Reduction of traditional demolition from 80.75% in 2020 to 50% in 2050 in the Baseline scenario and 95% in the Ambitious Circularity Scenario • The landfilling and backfilling processes and costs are modelled according to Caro et al. (2024) and the wet processing according to Etxeberria et al. (2022) and Zhang et al. (2019) • The 18% increase in recycling is subtracted in equal parts from landfilling and backfilling • Despite an overestimation of recycling due to the vague definition of backfilling (Moschen-Schimek et al., 2023), the official Eurostat numbers of construction and demolition waste (77%) used in Caro et al. (2024) are assumed • Recycled aggregates are substituting both gravel and sand, at a substitution rate of 0.97 for coarse aggregates (Bayram & Greiff, 2023; Iodice et al., 2021) and 0.86 for fine aggregates (Iodice et al., 2021; Le & Bui, 2020).
Limits and improvements	• Overestimation of recycling, rather than backfilling, due to non-harmonised data collection, different national waste code systems and unclear definition of backfilling (Cristóbal García et al., 2024; Moschen-Schimek et al., 2023) • Limited trust in recycled materials due to lack of certification, standards and legislation (Silva et al., 2017)

Source: JRC elaboration

2.2 Combination of levers

The levers are applied individually, in their CE cluster as well as all together. This will naturally result in a number of interactions between the levers that reduce the maximum effect of individual levers, meaning that the aggregated circularity is not the same as the sum or multiplication of the different levers. For identifying the interrelationships between the levers, the analyses of Milford et al. (2013) and Thung et al. (2024) were taken as an inspiration. The second study underlines the importance of applying the levers sequentially throughout the lifecycle and giving precedence to the higher R-ladder strategies, meaning that e.g. reduction should be prioritised over reuse and reuse over recirculation, where they are mutually exclusive (Thung et al., 2024). This is for instance the case, if levers are applied to the same construction type (e.g. buildings), or to the overall cement and concrete demand. The following matrix **Table A 14** specifies the interrelationships between the levers. In case the levers are combined at the same lifecycle stage in the modelling, their effect is multiplied, while, if the effects are mutually exclusive (either-or), they are added (e.g. if they address a share of the total demand, the lever effects are individually subtracted from the total demand and then added). ‘No interaction’ indicates that mass flows are not affected by the other lever. This is mainly the case for the end of life, given that a reduction in construction within a certain year, does not translate into a lower absolute demolition, due to the long life cycle of construction products. Only in the case of lifetime increase is the demolition rate directly reduced in the same year. At the end of life, there is also a trade-off between reuse and recycling after selective demolition, where precedence is given to reuse. Moreover, if the same product can be used to replace different primary materials (e.g. the recycled cement fines can replace calcareous marl and primary cement), the replacement was set to 50% of the mass for each of the two options. This was to account for the fact that the market is potentially interested in both the replacement of calcareous marl and cement, thus not only representing the result with the highest reduction potential (using cement fines as replacement of calcareous marl).

Table A 14. Razor matrix with interrelationships of circularity levers in maximum circularity scenario

CE lever	Clinker raw material substitution	Clinker substitution With SCM	Cement substitution with alternative binder	Concrete substitution with wood	Cement reduction	Concrete reduction	Lifetime increase	Concrete reuse	Recycle concrete to clinker raw material	Recycle concrete to cement	Recycle concrete to concrete
Clinker raw material substitution		combine	Either or	Either or	Combine	combine	Either or	No interaction	No interaction	No interaction	No interaction
Clinker substitution with SCM	combine		Either or	Either or	Combine	combine	Either or	No interaction	No interaction	No interaction	No interaction
Cement substitution with alternative binder	Either or	Either or		Either or	Combine	combine	Either or	No interaction	No interaction	No interaction	No interaction
Concrete substitution with wood	Either or	Either or	Either or		Either or	Either or	Either or	No interaction	No interaction	No interaction	No interaction
Cement reduction	combine	combine	combine	Either or		combine	Either or	No interaction	No interaction	No interaction	No interaction
Concrete reduction	combine	combine	combine	Either or	combine		Either or	No interaction	No interaction	No interaction	No interaction
Lifetime increase	Either or	Either or	Either or	Either or	Either or	Either or		Either or	Either or	Either or	Either or
Concrete reuse	No interaction	No interaction	No interaction	No interaction	No interaction	No interaction	Either or		Either or, reuse takes precedence	Either or, reuse takes precedence	Either or, reuse takes precedence
Recycle concrete to clinker raw material	No interaction	No interaction	No interaction	No interaction	No interaction	No interaction	Either or	Either or, reuse takes precedence		Either or, modelled as 50% / 50%	Either or, modelled with max. fines

Recycle concrete to cement	No interaction	No interaction	No interaction	No interaction	No interaction	No interaction	Either or	Either or, reuse takes precedence	Either or, modelled as 50% / 50%		Either or, modelled with max. fines
Recycle concrete to concrete	No interaction	No interaction	No interaction	No interaction	No interaction	No interaction	Either or	Either or, reuse takes precedence	Either or, modelled with max. fines	Either or, modelled with max. fines	

Source: JRC elaboration

We mitigated the risk of overestimating emission and material reductions by sequentially applying interventions of high R-ladder priority to low R-ladder priority on the modelled European construction sector. We took into account the interactions between interventions to avoid overestimating the total scenario effect, because failure to consider these interactions could lead to measuring advantages that are not realistically achievable, as buildings and/or products may sometimes be unable to undergo simultaneous adjustments from two interventions. For instance, a load-bearing structure cannot be made simultaneously of both innovative concrete and biobased material. Therefore, we modelled the interactions between interventions by sequentially adjusting the properties of the construction sector through the interventions, as described in **Figure 6**. The prioritisation of interventions was based on desirability according to the R-ladder (see table). For example, reducing construction has a greater impact than lifetime extension, as each square metre built results in more material usage and CO_2 emissions during the building's lifetime.

Annex 3. Life cycle inventory

Consult the two supplementary material files for the 1) product life cycle and 2) GECO 2023 energy mix according to Keramidas et al. (2023). The supplementary material is available upon request.

Annex 4. Values for epistemic uncertainty sensitivity analysis

The workshop determined the effectiveness of the lever in the alternative future through stress-testing the assumptions around the impact of CE clusters on material flows. For the analysis, the average of the low, medium and high range of effectiveness were taken, as reported in **Table A 15.** Values for epistemic uncertainty sensitivity analysis of prospective LCA. **Table A 15**. This table also contains the expected change in material flow due to the macroeconomic changes, as proposed by the experts in the sense-making session, in line with the narrative of the scenarios. The magnitude of the change is in line with the one proposed by Schandl et al. (2020), where the reference is the difference between the scenario in line with the historical trajectory (SSP2) and the other four scenarios that either exhibit growing or contracting economies.

Table A 15. Values for epistemic uncertainty sensitivity analysis of prospective LCA

	Material flow change	**Reduce**	**Reuse**	**Recover**
Glocal Eco-World **Collectivist / not supportive**	-20%	Medium 67%	High 82%	Medium 67%
Ecostates **Collectivist / supportive**	20%	High 82%	High 82%	High 82%
Green Business Boom **Individualist / supportive**	20%	Low 52%	Low 52%	High 82%
Greening through Crisis **Individualist / not supportive**	-20%	Low 52%	Medium 67%	Medium 67%

Source: JRC elaboration

Annex 5. LCA results of EF 3.1 impact categories

The relative reduction to the Baseline scenario (BSL50) calculated via LCA for the Ambitious Circular Economy scenario (ACE50), and the Reduce, Reuse, Recover clusters are reported in **Table A 16**.

Table A 16. Savings relative to the Baseline scenario (BSL50) calculated in % via LCA

Impact category	ACE50	Reduce	Reuse	Recover
Climate change	-38.4%	-28.7%	-8.4%	-3.4%
Ozone depletion	6.0%	7.6%	-8.1%	7.9%
Human toxicity, cancer effects	-15.7%	-9.7%	-8.2%	0.6%
Human toxicity, non-cancer effects	-10.4%	-2.7%	-8.5%	0.4%
Particulate matter	44.0%	40.7%	-7.2%	12.4%
Ionising radiation	51.0%	59.5%	-8.6%	-0.7%
Photochemical ozone formation	6.5%	3.8%	-7.2%	11.9%
Acidification, terrestrial	-1.0%	-0.1%	-7.6%	7.8%
Eutrophication, terrestrial	0.1%	-1.9%	-7.2%	11.1%
Eutrophication, freshwater	51.4%	58.8%	-8.4%	-0.3%
Eutrophication, marine	3.9%	0.9%	-7.1%	12.3%
Ecotoxicity, freshwater	-16.0%	-9.5%	-8.4%	1.3%
Land use	428.6%	437.1%	-8.4%	-1.2%
Water use	5.2%	13.8%	-8.4%	-1.1%
Resource use, minerals and metals	-12.3%	-0.7%	-8.6%	-1.8%
Resource use, energy	11.9%	13.0%	-7.8%	8.4%

Note: ACE50 stands for Ambitious Circular Economy scenario

Source: Own calculations

The relative reductions to the BSL50) for the individual CE levers considered in the study are reported in **Table A 17**.

Table A 17. Savings of implemented relative to the Baseline scenario (BSL50) calculated in %, via LCA

	Reduce						Reuse		Recover		
Impact category	L(1)	L(2)	L(3)	L(4)	L(5)	L(6)	L(7)	L(8)	L(9)	L(10)	L(11)
Climate change	-1.0%	-14.8%	-6.6%	3.4%	-1.4%	-14.4%	-8.1%	-0.4%	-2.5%	-1.4%	0.1%
Ozone depletion	-0.3%	0.5%	-0.6%	21.2%	-0.6%	-13.1%	-8.3%	0.3%	7.5%	6.9%	0.2%
Human toxicity, cancer effects	-0.1%	-20.4%	-1.8%	23.6%	-1.2%	-14.9%	-8.0%	-0.2%	1.2%	0.3%	-0.2%
Human toxicity, non-cancer effects	-0.1%	-4.1%	-1.6%	17.3%	-0.9%	-14.8%	-8.1%	-0.5%	1.5%	-0.1%	-0.2%
Particulate matter	-0.2%	-9.5%	-0.2%	62.0%	-0.8%	-13.1%	-8.3%	1.2%	11.4%	10.5%	1.3%
Ionising radiation	-0.1%	-3.2%	0.1%	79.1%	-0.6%	-16.8%	-7.9%	-0.8%	1.2%	0.0%	-1.9%
Photochemical ozone formation	-0.3%	-7.9%	-0.2%	24.0%	-0.8%	-13.4%	-8.2%	1.2%	11.1%	10.1%	1.2%
Acidification, terrestrial	-0.2%	-8.6%	-0.5%	21.5%	-1.0%	-13.9%	-8.2%	0.6%	7.8%	6.3%	0.8%
Eutrophication, terrestrial	-0.3%	-8.9%	-0.2%	19.5%	-0.9%	-13.6%	-8.2%	1.1%	10.7%	9.2%	1.3%
Eutrophication, freshwater	-0.1%	-15.7%	-1.5%	88.0%	-1.3%	-14.9%	-8.0%	-0.4%	0.9%	-1.1%	-0.1%
Eutrophication, marine	-0.3%	-8.3%	-0.2%	21.6%	-0.9%	-13.5%	-8.2%	1.3%	11.6%	10.2%	1.4%
Ecotoxicity, freshwater	-0.1%	-11.4%	-1.0%	15.2%	-1.3%	-14.3%	-8.1%	-0.3%	2.8%	0.0%	0.1%
Land use	-0.1%	-11.1%	-1.1%	462.6%	-1.1%	-15.2%	-8.0%	-0.5%	0.5%	-1.9%	-0.2%
Water use	-0.2%	-7.9%	-1.4%	37.3%	-1.1%	-15.4%	-8.0%	-0.5%	0.7%	-1.5%	-0.4%
Resource use, minerals and metals	-0.1%	-4.8%	23.1%	0.8%	-1.3%	-15.0%	-8.0%	-0.7%	0.3%	-3.0%	0.0%
Resource use, energy	-0.3%	1.6%	-0.5%	25.7%	-0.6%	-13.2%	-8.3%	0.5%	8.1%	7.4%	0.3%

Note: (L1) corresponds to Raw material substitution, (L2) to Clinker substitution, (L3) to Cement substitution, (L4) to Concrete substitution, (L5) to Cement reduction, (L6) to Concrete reduction, (L7) to Lifetime extension, (L8) to Concrete reuse, (L9) to Recycling to raw material, (L10) to Recycling to cement, and (L11) to Recycling to aggregates

Source: Own calculations

Annex 6. Criteria for IO model selection

To fit the purpose of this study, the IO model should be regularly updatable and verifiable by EU Commission services. The scope of the IO model should cover the global economy but should at least allow to separate impacts inside and outside the EU27. A higher sector disaggregation is preferred, especially a disaggregation of sectors linked to the selected case studies is considered an added value. The development of a disaggregation methodology is part of the methodology which allows to overcome the issue of too aggregated sector classifications. Also, either the use of product-by-product tables or the use of industry-by-industry tables is considered. Finally, it should be kept in mind that the selected model will be expanded to include dynamic analysis. The pre-existence of such a link (e.g., between FIGARO and FIDELIO) is a plus.

We prefer to first decide on the selection of the most appropriate monetary IO-model without considering the availability of environmental and other extensions. In case the selected model does not include sufficient coverage of environmental and other extensions, an additional step is needed to add the missing data via alternative sources (in Task 2.3). The reason to focus in a first step only on the monetary tables, is that it will allow to select the most appropriate, updatable, and high-quality IO model available fitting the purpose of this study and future work within the JRC. A minimum requirement for the IOA is to use tables that are widely available and known to the scientific community. The options would be too limited if the availability of environmental and other extensions is considered already in this decision step.

The following models are considered:

- **FIGARO** (the 2024 FIGARO edition)[20]: The EU inter-country supply, use and input-output tables (developed by Eurostat and the JRC) are part of official EU statistics (2000-2021 data). The FIGARO tables are benchmarked against the most recent macroeconomic aggregates and respect the same quality standards as official statistics and are released annually by Eurostat (T-2). The tables present the relationship between the EU27 and 18 non-EU countries plus a rest of world region, covering 64 industries (NACE rev.2 classification).

  Extension data in FIGARO: **Air emissions accounts** are collected under Regulation (EU) No 691/2011 on European Environmental Economic Accounts. Air emission accounts are compiled according to the system of environmental economic accounting and can therefore be readily combined with input-output tables for further analysis (assuming the use of industry-by-industry tables). The data on **employment** for each EU Member State at the level of 64 industries (based on NACE Rev. 2) are expressed in numbers of persons employed. These data are collected via the European system of accounts (ESA 2010) transmission programme and are available on Eurostat's website [nama_10_a64_e].

  Note: These data sources are restricted to EU-27 data (and in addition UK-data), but do not cover data for non-EU countries.

- **FIGAROe3**[21] is a comprehensive inter-country supply, use, and input-output database for 2015, featuring labour and environmental extensions that are in line with official statistics. The database encompasses data for 213 products and 176 industries across 45 geographical areas (country disaggregation is equal to FIGARO), as well as one aggregated rest of

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[20] https://ec.europa.eu/eurostat/web/esa-supply-use-input-tables/information-data#figaro

[21] https://data.jrc.ec.europa.eu/collection/id-00403

the world region. Labour accounts detail total employment and employment broken down by gender and skill level. Energy accounts include primary energy supply and net energy use, while air emission accounts cover four types of greenhouse gases - CO2, CH4, N2O, and fluorinated gases - for both combustion and non-combustion processes.

- **EXIOBASE**[22]: v3.8.2/v4 includes a timeseries of supply, use and input-output tables covering 1995-2022. The 163 sectors and 200 products disaggregation provide highly detailed sector/product relations between the EU27 MS, 17 non-EU countries and 5 rest of world regions. The wide coverage of environmental extensions allows to (partly) cover 14 out of the 16 environmental impact categories[23] as well as employment. Hybrid versions and country extended versions of EXIOBASE (EXIOBASE3rx[24]) exist as well.
- **OECD harmonised national Input-Output Tables (OECD IOT tables)**[25]: Inter-industrial flows of goods and services for 76 countries (all OECD countries and several non-member economies (including all G20 countries)) and 45 sectors, covering the time-period 1995-2020 are available. Extension tables only cover CO_2-emissions from fuel combustion.

Based on the above listed characteristics, the use of either FIGARO or FIGAROe3 are both considered as the most suitable models in this project. FIGARO has the drawback of the limited sector disaggregation, while FIGAROe3 is currently only available for the year 2015. **The project team's preference goes to the use of FIGAROe3 model. It is the model best in line with the needs of this project.** Still, the methodology will be developed in such a way that it will be applicable to the more common IO-tables. The following issues were considered in making this choice:

- **Up-to-date multiregional input-output model covering at least the EU27 region and other major economies in the world:** Both the FIGARO and the OECD IOT tables are regularly updated as both are institutionalised in Eurostat and OECD, respectively. The FIGAROe3 has currently only data for one year, namely 2015. The development of a time-series version of this experimental dataset is being planned. EXIOBASE is the culmination of work in the FP7 DESIRE project and builds upon earlier work on EXIOBASE 2 in the FP7 CREEA project and EXIOBASE 1 of the FP6 EXIOPOL project. Future updates are infrequent and uncertain. The latest data year for FIGARO is 2021; for FIGAROe3 is 2015; for EXIOBASE is 2022 (based on nowcasting); and for OECD IOT tables is 2020.
- **The model should be verifiable by EU Commission services**: The FIGARO tables are benchmarked against the most recent macroeconomic aggregates and respect the same quality standards as official statistics and are released annually by Eurostat. Also, FIGAROe3 is line with official European statistics. This quality is not guaranteed in the use of EXIOBASE or the OECD IOT tables.
- The scope of the IO model should cover the global economy but should at least allow to separate impacts inside and outside the EU27: All models (FIGARO, FIGAROe3, EXIOBASE

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[22] Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., ... Tukker, A. (2021). EXIOBASE 3 (3.8.2) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.5589597

[23] Correspondence tables are found here and here.

[24] Bjelle, Stadler, & Wood. (2019). EXIOBASE 3rx (1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.2654460

[25] https://www.oecd.org/sti/ind/input-outputtables.htm

and OECD IOT tables) include the EU27 member states and the rest of the world, although the country aggregation differs between the models.

- A higher sector disaggregation is preferred, especially a disaggregation of sectors linked to the selected case studies is considered an added value: The highest sector disaggregation is available in the FIGAROe3 model covering 176 sectors (and 213 product groups). Also, EXIOBASE uses a higher sector disaggregation level, detailing 163 sectors (and 200 product groups). Both the FIGARO and the OECD IOT tables use a more aggregated sectors classification, detailing only 64 and 45 sector groups, respectively. This project case studies focus on steel, aluminium, plastics, cement, and textiles. A first analysis focussing on mining, manufacturing and end-of-life treatment of each case study shows a difference in the relevance of sector disaggregation between the different IO models.
    - The limited sector detail in FIGARO and the OECD IOT tables doesn't allow to directly link the model to the case studies. The mining step is aggregated into mining and quarrying (in FIGARO) or into non-energy producing products (in OECD IOT). In manufacturing, only for the case of textiles one separate manufacturing step is available. Waste management is aggregated into the sector group 'Water supply, sewerage, waste management and remediation activities'.
    - Both FIGAROe3 and EXIOBASE have a much higher detail in their sector classification allowing to make a distinction between mining sectors (e.g., the mining of iron ores and aluminium ores are covered by separated sectors) and in manufacturing already some level of detail is available per case study (e.g., a distinction between textile production and production of wearing apparel is made). Also, for most cast studies a first distinction between primary and secondary production is available. Multiple steps in the waste management system are available.
- **The use of product-by-product tables or the use of industry-by-industry tables is considered:** The OECD IOT tables are only available following the industry-by-industry approach. FIGARO, FIGAROe3 and EXIOBASE are all available in both the industry-by-industry approach and the product-by-product approach.
- **The availability of environmental and social extension tables is a plus:** None of the IO models already include all the necessary environmental and social extension tables. EXIOBASE is the model with the most expanded set of mainly environmental extensions. In contrast, FIGARO doesn't include extension data, but its structure easily allows linkages to existing (official) EU datasets. FIGAROe3 covers extension data on employment, energy, and air emissions. The extension tables of the OECD IOT tables only cover CO_2-emissions from fuel combustion.
- **The selected model will be expanded to include dynamic analysis. The pre-existence of such a link is a plus:** There is a link between FIGARO (and FIGAROe3) and the dynamic econometric IO model FIDELIO. No link with a dynamic model is available for EXIOBASE or the OECD IOT tables.

Annex 7. FIGAROe3

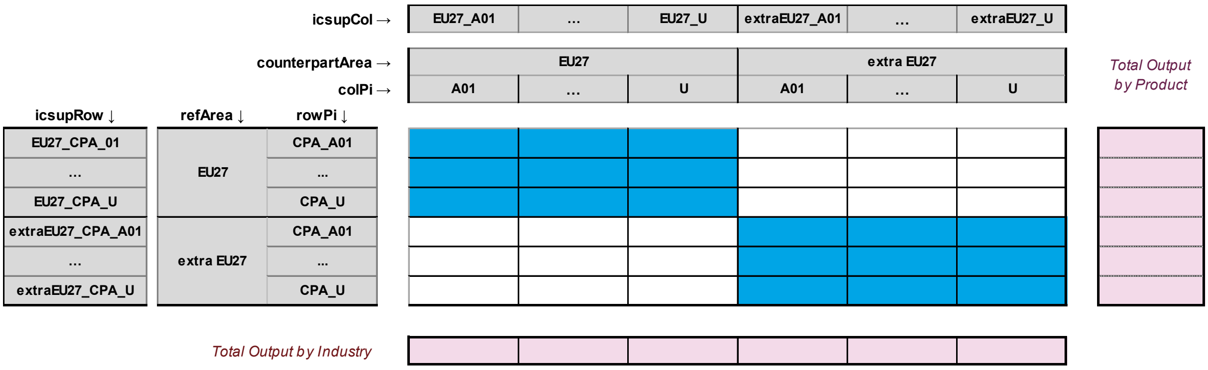
The **monetary supply and use tables** from the **FIGAROe3** model cover 45 geographical areas plus one rest-of-the-world (FIGW1) region. Per region the model details 213 products and 176 industries. Labour accounts detail total employment and employment broken down by gender and skill level. Energy accounts include primary energy supply and net energy use, while air emission accounts cover four types of greenhouse gases - CO2, CH4, N2O, and fluorinated gases - for both combustion and non-combustion processes.

The geographical areas covered by FIGAROe3 are the EU27 Member States and the individual countries Argentina, Australia, Brazil, Canada, Switzerland, China, Indonesia, India, Japan, South Korea, Mexico, Norway, Russia, Saudi Arabia, Turkey, United Kingdom, United States, and South Africa. In addition, one aggregated rest of the world region (FIGW1) is added to cover the full world economy.

The products classification in the FIGAROe3 model is linked to the CPA 2.1 nomenclature. The sector classification is linked to the NACE 2.1 nomenclature. The CPA product categories are related to the economic activities of the statistical classification of economic activities (NACE).

An **inter-country supply table** (matrix representation shown in Figure 32) shows the supply of goods and services by type of product of an economy for a given period. Each column shows the output per sector (in NACE classification) disaggregated into different products (in CPA classification). As each sector can supply multiple products, the supply table is heterogeneous. The column headings show an area code (counterpartArea) and a sector classification code (colPi). The row headings show an area code (refArea) and a product classification code (rowPi). The column totals show the total output per sector; the row totals show the total output per product. Only the cells highlighted in blue will show observed values.

Figure A 1. Schematic presentation of an **inter-country supply table**, detailing two geographical areas (EU27 and non-EU27)



		icsupCol →	EU27_A01	…	EU27_U	extraEU27_A01	…	extraEU27_U	
		counterpartArea →	EU27			extra EU27			*Total Output by Product*
		colPi →	A01	…	U	A01	…	U	
icsupRow ↓	refArea ↓	rowPi ↓							
EU27_CPA_01	EU27	CPA_A01	🟦	🟦	🟦				
…		…	🟦	🟦	🟦				
EU27_CPA_U		CPA_U	🟦	🟦	🟦				
extraEU27_CPA_A01	extra EU27	CPA_A01				🟦	🟦	🟦	
…		…				🟦	🟦	🟦	
extraEU27_CPA_U		CPA_U				🟦	🟦	🟦	
		Total Output by Industry							

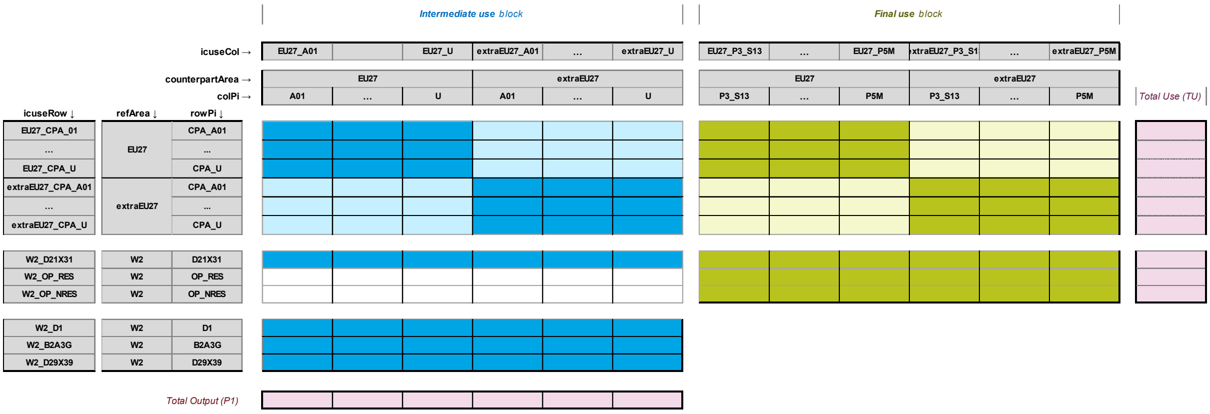
Source: Based on FIGARO description tables

An **inter-country use table** (matrix representation shown in Figure 33) shows the use of goods and services by type of product (in CPA classification) per sector (in NACE classification) of an economy for a given period. The use of domestically produced goods and services is shown in the dark coloured areas on main diagonal, separately for intermediate use (blue) and for final use (green). The light areas represent, vertically, the intermediate (blue) and final use (green) use of goods and services produced abroad (imports). In contrast, when presented horizontally they represent exports broken down by user and by trading partner.

The use table is supplemented with data on tax less subsidies (AB21x31), direct purchases abroad by residents (OP_RES), and non-resident purchases in the territory (OP_NRES). The components of value added are compensation of employees (D1), other taxes less subsidies on production (AB29x39), and gross operating surplus and mixed income (B2A3G).

The final demand is disaggregated into final demand categories: government consumption (P3_S13), consumption of households (P3_S14), consumption of non-profit institutions serving households (NPISH; P3_S15), gross fixed capital formation (P51G), and changes in valuables and inventories (P5M).

Figure A 2. Schematic presentation of an **inter-country use table**, detailing two geographical areas (EU27 and non-EU27)



Source: Based on FIGARO description tables

The monetary values in the supply and use tables show **basic prices** (in million euros, current prices). A full description of the inter-country supply and use tables is given in the FIGARO manual[26] (2019-edition).

The FIGAROe3 database is downloaded from the Joint Research Centre Data Catalogue[27]. This includes the download of the inter-country supply and use matrices ().

Table A 18. FIGAROe3 data download

Name	Data provider	Type	Last update	Unit
Inter-Country Supply Matrix	FIGAROe3 by JRC	CSV-file	27/02/2024	Basic prices, in million euros
Inter-Country Use Matrix	FIGAROe3 by JRC	CSV-file	27/02/2024	Basic prices, in million euros

Note: Ensure values are correctly read by the software of choice (Excel, R ...). Commas are used to separate values; decimal points indicate decimal numbers

Source: JRC elaborations

The FIGAROe3 inter-country supply and use tables (in matrix format) can be directly imported in R using the read.csv()-function. The tables have one row with column headers and one column with row labels, commas are used to separate values, and decimal points are used to indicate decimal numbers.

If the column headers are read in as variable names, the FIGAROe3 supply table has 9,798 rows (213 product categories * 46 regions) and 8,097 columns (1 row labels column + 176 industries * 46 regions). Similarly, the FIGAROe3 use table has 9,809 rows (213 product categories * 46 regions

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[26] European Commission, Eurostat, Rémond-Tiedrez, I., Rueda-Cantuche, J., EU inter-country supply, use and input-output tables – Full international and global accounts for research in input-output analysis (FIGARO) – 2019 edition, Rémond-Tiedrez, I.(editor), Rueda-Cantuche, J.(editor), Publications Office, 2019, https://data.europa.eu/doi/10.2785/385561

[27] https://data.jrc.ec.europa.eu/collection/id-00403#details

+ 11 domestic rows) and 8,327 columns (1 row labels column + 176 industries * 46 regions + 5 final use categories * 46 regions).

The **inter-country input-output tables** of FIGARO are compiled using the standard assumptions for all countries. From inter-country supply and use tables, two inter-country input-output tables are created following the analytical transformation processes for deriving the input-output tables[28]: inter-country product-by-product input-output tables and inter-country industry-by-industry input-output tables.

- **Model B** (industry technology assumption) is applied to derive the industry technology product-by-product input-output tables.
- **Model D** (fixed product sales structure assumption) is applied to derive the fixed product sales structure industry-by-industry input-output tables.

The inter-country input-output tables are not downloaded but are directly created in the R-software. During the modelling of the scenarios, changes will be applied to the inter-country supply and/or use tables (and/or to the extension tables). After these changes are applied, a new inter-country input-output table is generated via the same analytical transformation process as the original inter-country input-output table.

A quality check is done to compare the self-created inter-country input-output table starting from the downloaded inter-country supply and use tables and the inter-country input-output table from the JRC data catalogue. Only minor deviations due to rounding differences are found (absolute value of deviations typically below 0.001).

Annex 8. Input-output analysis

The global distribution of pressures and effects related to final consumption of households have been calculated using an extended multiregional input-output models. For this purpose, environmentally extended industry-by-industry tables were used. The calculation started from the following identities:

$$x = A \cdot x + y \qquad (1)$$

where x is the total output vector, A the matrix of direct input coefficients (or matrix of technological coefficients), and y is the final demand vector. Solving the model for output gives:

$$x = (I - A)^{-1} \cdot y = L \cdot y \qquad (2)$$

with identity matrix I, and matrix L the Leontief inverse also known as the multiplier matrix or matrix of direct and indirect output requirements per unit produced for final demand. The Leontief model implies the following assumptions: prices are fixed in the short term, input coefficients are constant regardless of output or final demand level changes, structure of the economy is taken to be constant, at least in the reported period.

The direct environmental effects of national production are the result of the sum of the direct effects associated with each unit produced in each industry:

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[28] Eurostat (2008), Eurostat Manual of Supply, Use and Input-Output Tables, Publications Office of the European Union, Luxembourg

$$E^T = \sum_1^n E_t = \sum_1^n e_t^{int} = \langle e^{int} \rangle \cdot x \qquad (3)$$

where E^T is the total environmental or socio-economic effect associated with the corresponding amounts of the final output x and e^{int} is the environmental or socio-economic effect intensity vector. Each element of e^{int} represents the amount of the effect directly caused by the production of a product group. By multiplying the environmental pressure per output unit (measured in physical units per euro worth of output) by the total output of each industry (measured in million euro), defined by equation (2), an environmentally extended input-output model is created:

$$E^T = \langle e^{int} \rangle \cdot x = \langle e^{int} \rangle \cdot (I - A)^{-1} \cdot y \qquad (4)$$

in which E^T is the vector of total environmental pressures associated with the corresponding amounts of the products groups finally used (vector y) and e^{int} the environmental pressure intensity vector. Each element of e^{int}represents the amount of the environmental pressure directly caused by the production of a product group. Each element of e^{int} is allocated to a sector-region combination, which, for example, allows to derive the EU-27 shares in the total footprint.

The global distribution of pressures and effects related to the final EU27 consumption have been calculated using an extended multiregional input-output model based on FIGAROe3 (industry-by-industry tables). The calculation is based on the following formula:

$$E_{ind}^T + E_{dir}^T = \langle e^{int} \rangle . x + E_{dir}^T = \langle e^{int} \rangle . (I - A)^{-1} . y + E_{dir}^T$$

with:

- E_{ind}^T: environmental footprint (indirect impacts)
- E_{dir}^T: environmental footprint (direct impacts generated by final demand)
- $\langle e^{int} \rangle$: environmental effect intensity vector, the amount of the effect directly cased by the production of a product group
- x: sectoral (monetary) output
- $(I - A)^{-1}$: Leontief inverse, representing the economic structure of the supply chain network
- y: final demand, EU-27

The scope includes both indirect and direct impacts/resource use. The indirect impacts/resource use covers impacts upstream the global production network. It covers impacts from all kinds of activities, for example, manufacturing, agriculture, and transport. The direct impacts/resource use covers impacts directly generated by households. For example, the burning of fuels for heating houses or driving a car.

Applying the formula gives individual results for each environmental extension available from the FIGAROe3-dataset.

Applying the formula results in a single value output. It is the total impacts (direct and indirect) related to EU-27 final demand. To increase the details of the results, one needs to diagonalise either the environmental coefficient vectors, or the final demand vector, both result in a column and row vector respectively. Diagonalising the coefficient vector results in a column vector detailing by which region (geographically) and by which sector the impact is generated. Diagonalising the final demand vector results in a row vector detailing by which consumption (per region and per sector output) the impact is triggered. Diagonalising both the coefficient vector and the final demand vector results in an output matrix detailing both the origin of impacts and their triggers. Due to the large resolution of this matrix, this latter output is not preferred.

Annex 9. Implementation of the MFA and LCI for the IO analysis

As first step, cement and concrete flows are matched with the corresponding product categories available in FIGAROe3 and presented in **Table A 19**. Based on the comparison with the results from the material flow analysis, a proposal for sector and product disaggregation is made.

Table A 19. Matching of MFA flows and FIGAROe3 categories

FIGAROe3 code	FIGAROe3 name	Corresponding MFA flow	Type
CPA_B05_C	Other Bituminous Coal	Coal for combustion	Energy
CPA_B07_E	Copper ores and concentrates	Bauxite	Material
CPA_B08_A	Stone	Gravel	Material
CPA_B08_B	Sand and clay	Sand and clay	Material
CPA_B08_C	Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	Calcareous marl, limestone	Material
CPA_C16_A	Wood and products of wood and cork (except furniture), articles of straw and plaiting materials	Timber substituting concrete and biomass for energy	Material, energy
CPA_C192_F	Gas/Diesel Oil	Diesel	Energy
CPA_C21	Chemicals n.e.c.	Ammonia, ethylene glycol	Material
CPA_C23_E	Cement, lime and plaster	Clinker, cement and SCMs, concrete (to be disaggregated)	Material
CPA_C23_F	Ash for treatment, Re-processing of ash into clinker	SCMs (to be combined with C23_E due to small size)	Material
CPA_C24_A	Basic iron and steel and of ferro-alloys and first products thereof	Steel	Material

CPA_D3511_A	Electricity by coal	Electricity by coal	Energy
CPA_D3511_B	Electricity by gas	Electricity by gas	Energy
CPA_D3511_C	Electricity by nuclear	Electricity by nuclear	Energy
CPA_D3511_D	Electricity by hydro	Electricity by hydro	Energy
CPA_D3511_E	Electricity by wind	Electricity by wind	Energy
CPA_D3511_F	Electricity by petroleum and other oil derivatives	Electricity by petroleum and other oil derivatives	Energy
CPA_D3511_G	Electricity by biomass and waste	Electricity by biomass and waste	Energy
CPA_D3511_H	Electricity by solar photovoltaic	Electricity by solar photovoltaic	Energy
CPA_D3511_I	Electricity by solar thermal	Electricity by solar thermal	Energy
CPA_D3511_J	Electricity by tide, wave, ocean	Electricity by tide, wave, ocean	Energy
CPA_D3511_K	Electricity by Geothermal	Electricity by Geothermal	Energy
CPA_D3511_L	Electricity n.e.c.	Electricity generic	Energy
CPA_D352_F	Distribution services of gaseous fuels through mains	Natural gas	Energy
CPA_D353	Steam and hot water supply services	Industrial heat	Energy
CPA_E36	Collected and purified water, distribution services of water	Tap water	Material
CPA_F_A	Construction work	Construction of buildings, infrastructure & maintenance	Service
CPA_H49_B	Other land transportation services	Transport	Service

Source: JRC elaborations

A disaggregation of the sector related to cement and concrete is required to allow for a better linkage between the results from the MFA and modelling of changes in the supply and use tables. The sector disaggregation includes, first, to make the sum of the existing sectors 'Manufacture of cement, lime and plaster' (C23_E) and 'Manufacture of ash for treatment, Re-processing of ash into clinker' C23_F), and second to disaggregate these sectors into 21 subsectors, depicted in **Table A 1**.

Table A 20. Disaggregated sectors with respective market prices.

Adapted NACE code	Production sector	Estimated market price in EUR2020/kg
C23_EF1	Clinker production	0.0520
C23_EF2	SCM production	0.0097
C23_EF3	Blast furnace slag production	0.0251
C23_EF4	Gypsum production	0.0097
C23_EF5	Limestone production	0.0080
C23_EF6	Calcined clay production	0.0642
C23_EF7	CEMI production	0.1077
C23_EF8	CEMII production	0.1077
C23_EF9	CEMIII production	0.1077
C23_EF10	CEM generic production	0.1077
C23_EF11	CEM low carbon production	0.1077
C23_EF12	Alternative binders production	0.2154
C23_EF13	Pre-cast concrete production	0.0719
C23_EF14	Ready-mixed concrete production	0.0719
C23_EF15	Plaster & mortar production	0.0719
C23_EF16	Selective demolition	0.0195
C23_EF17	Traditional demolition	0.0195
C23_EF18	Alternative Dry Recovery recycling (ADR)	0.0195
C23_EF19	Wet recycling	0.0195
C23_EF20	Heating Air classification System recycling (HAS)	0.0195
C23_EF21	others	NA

Note: the estimated market price is derived from ESTAT import statistics (in kilogram per euro) of a comparable product for the year 2015

Source: JRC elaborations

The 'C23_EF21 others' is added to keep the balance in the supply and use tables. It is added to entail the (minor) supply of other non-cement and non-concrete products as mentioned by the original sector (C23_E + C23_F) sector in FIGAROe3. Via this 'others' sector, the original balance of the FIGAROe3 model is maintained.

The product disaggregation includes the disaggregation of the corresponding products CPA_C23_E and CPA_C23_F into the 21 categories mentioned above.

Next to the cement and concrete inputs, the newly added sectors have other (non-cement & concrete) inputs which need to be included in the use table in order to complete the 'production recipe'. The input structure for sectors EF1 to EF20 is based on data based on life cycle inventories of the LCA.

First, the inputs of resources, materials, fuels, electricity, and heat is scaled to the sector size and converted into monetary units. Each input is linked to one or multiple CPA-codes of the FIGAROe3 classification. The data is included in the Excel-file in black.

After converting all the inputs from the LCI-data into the FIGAROe3 CPA-nomenclature, still many inputs (e.g. input of services) remain unspecified. For these inputs, the original values from the FIGAROe3 sector C23_E and C23_F are used and spread across the disaggregated sectors based on the monetary output shares. The CPA-codes related to cement & concrete flows are left unaltered, as these are already based on data from the material flow analysis or from the life cycle inventories of the LCA.

The result is transferred into the use table. To do this, the data needs to be split across domestic (i.e. EU27) consumption and imports. This split is based on the original data from FIGAROe3. Afterwards, the RAS method is applied to balance the tables. Finally, at this point, the disaggregated supply and use table (both product and sector level detail) is increased to increase the granularity of the model specifically for the case-related sectors/products. Next, the model is regionally disaggregated again to return to the initial geographical detail of FIGAROe3.

Annex 10. Extension tables

10.1 Extension tables – Environmental Footprint

The **Environmental Footprint** (EF) method includes 16 impact categories. The elementary flows need to be converted into environmental impacts using a matrix of characterisation factors. Ionizing radiation and ozone depletion are excluded because emissions related to these impact categories are missing. A matrix of characterization factors reports the impact intensity per unit of resource extracted or substance emitted in the environment. Beylot et al. (2019)[29] make use of 78 elementary flows to estimate 14 out of the 16 environmental impact categories. VITO created a matrix of characterisation factors in the ETC/CE project of the Consumption Footprint indicator commissioned by the EEA, translating the 528 unique environmental extension lines from EXIOBASE v3.8.2 into 14 out of the 16 impact categories of the EF-method requires a conversion through characterisation factors.

The Environmental Footprint method includes the 16 environmental impact categories, as follows (the description is taken from Andreasi Bassi et al., 2023[30]):

- **CC**, **climate change**: Global impact due to changes induced to the climate, including increased average global temperatures and sudden regional climatic changes, as a consequence of the emissions to the atmosphere of the so-called greenhouse gases, such as CO_2, CH_4, and N_2O.
- **ODP**, **ozone depletion**: Global impact related to the broken-down of stratospheric O_3, including increased skin cancer cases in humans and damage to plants, as a consequence of

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[29] Beylot, A., Secchi, M., Cerutti, A., Merciai, S., Schmidt, J., Sala, S., 2019. Assessing the environmental impacts of EU consumption at macro-scale. J. Clean. Prod. 216, 382–393. https://doi.org/10.1016/j.jclepro.2019.01.134

[30] Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., et a., Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/798894, JRC130796

man-made emissions of halocarbons (as CFCs and HCFCs), halons, and other long-lived gases containing chloride and bromine.

- **HTOX_nc**, **human toxicity, non-cancer**: Local and regional impact to humans due to the exposure (i.e. due to inhalation of air, drinking water, etc.) to toxic substances emitted in the environment and responsible for diseases (e.g. respiratory disease) other than cancer.
- **HTOX_c**, **human toxicity, cancer**: Local and regional impact to humans due to the exposure to toxic substances emitted in the environmental and responsible for cancer effects.
- **PM**, **particulate matter**: Impact on human health due to the increased ambient concentrations of particulate matter (PM) due to the emissions of primary and secondary particulates (i.e. precursors, NO_x, SO_2).
- **IR**, **ionising radiation**: Impact to human health due to the exposure to ionising radiation (radioactivity) under normal operating conditions (i.e. excluding accidents in nuclear plants)
- **POF**, **photochemical ozone formation**: Local and regional impact to the environment and human health related to the formation of tropospheric ozone resulting from the oxidation of solvents and other volatile organic compounds (VOCs) released to the atmosphere that affects organic compounds in animals and plants and can increase the frequency of respiratory problems.
- **AC**, **acidification**: Regional impact to the environment regarding the modification of acidity of soils, as consequences of emission and deposition of acids (and compounds that can be converted to acids) into the environment.
- **TEU**, **eutrophication, terrestrial**: Local and regional impact on the terrestrial ecosystems due to substances containing nitrogen (N) or phosphorus (P) which leads to the disappearance of ecosystems that are poor in nutrients.
- **FEU**, **eutrophication, freshwater**: Local and regional impact on the freshwater ecosystems due to substances containing phosphorus (P) which leads to the reduced oxygen availability consequent from increased algal growth.
- **MEU**, **eutrophication, marine**: Local and regional impact on the marine ecosystems due to substances containing nitrogen (N) which leads to reduced oxygen availability consequent from increased algal growth.
- **LU**, **land use**: Impacts due to the effects of occupation and transformation of land in terms of reduction of soil qualities (e.g. modification in the organic matter content of soil, or loss of the soil itself (erosion))
- **ECOTOX**, **ecotoxicity freshwater**: Local and regional impact to freshwater ecosystem due to the release of toxic substances that can accumulate and affect individual species as well as the functioning of the entire ecosystem.
- **WU**, **water use**: Impact related to the consumption of freshwater (lakes, rivers, or groundwater)
- **FRD**, **resource use, fossils**: Global impact related to the decreased availability and the potential scarcity for future generations of the total reserve of fossil resources.

- **MRD**, **resource use, minerals and metals**: Global impact related to the decreased availability and the potential scarcity for future generations of the total reserve of mineral and metal resources.

A detailed description of each impact category can be found in Annex 1 of Andreasi Bassi et al. (2023).

Those impacts might ultimately lead to impairment of human health, biodiversity and natural resource loss, climate change, land use, water use, etc. These 16 impact categories can be normalized and weighted into a single weighted score[31] (see factors in **Table A 21**). Normalization means that all impact indicators are multiplied by normalization factors that represent the overall impact of a reference unit (e.g. a whole country or an average citizen). Normalized results based on the Environmental Footprint method express the relative shares of the impacts of EU consumption by citizens compared to global impacts (per person). Weighting means that all impact indicators are given a weight factor that expresses the 'importance' of the impact compared to the others. This allows the aggregation (summing up) of all impact indicators in one single value.

Table A 21. Normalisation and weighting factors of the Environmental Footprint method version 3.1

EF Impact Category	Unit	Normalization factor (EF-method 3.1)	Weighting factor
Climate change	kg CO2 eq	7553.0832	0.2106
Ozone depletion	kg CFC11 eq	0.0523484	0.0631
Ionising radiation	kBq U-235 eq	4220.1634	0.0501
photochemical ozone formation	kg NMVOC eq	40.859198	0.0478
Particulate Matter	disease inc.	0.0005954	0.0896
Human toxicity, non-cancer	CTUh	0.0001287	0.0184
Human toxicity, cancer	CTUh	1.725E-05	0.0213
Acidification	mol H+ eq	55.569541	0.062
Eutrophication, freshwater	kg P eq	1.6068521	0.028
Eutrophication, marine	kg N eq	19.545182	0.0296
Eutrophication, terrestrial	mol N eq	176.755	0.0371
Ecotoxicity, freshwater	CTUe	56716.586	0.0192
Land use	Pt	819498.18	0.0794
Water use	m3 depriv.	11468.709	0.0851
Resource use, fossils	MJ	65004.26	0.0832
Resource use, minerals, and metals	kg Sb eq	0.0636226	0.0755

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[31] In this study we apply the EF 3.1 normalisation and weighting factors, see https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html

Source: EF 3.1 (Andreasi Bassi et al., 2023)

A wide coverage of environmental extensions is available from the **EXIOBASE** (currently v3.8.2) dataset. The wide coverage allows to calculate 14 out of the requested 16 impact categories form the EF-method. Ionizing radiation and ozone depletion are excluded because emissions related to these impact categories are missing. Whereas the EF-method also recommends assessing the impacts in terms of ionizing radiation and ozone depletion, these two impact categories are excluded from this study. Indeed, in EXIOBASE coefficients relative to ionizing radiations are missing while ozone-depleting substances very often lack a value as well (Beylot et al., 2019).

A remark here is that the EF-method defines characterization factors for more emissions and resources extracted than available in EXIOBASE. For some environmental impacts, like climate change, the coverage of EXIOBASE is quite complete. For other impacts however, like toxicity, EXIOBASE includes only a very limited selection of emissions. No information, and thus no extension lines, is available in EXIOBASE to estimate the impact categories ozone depletion and ionising radiation.

Beylot et al. (2019):
Firstly, when it was not possible to match one EXIOBASE extension to a flow in EF2017, a proxy CF was introduced. The selection of the proxy was based on the same pollutants group (e.g. Persistent Organic Pollutants and Persistent Bioaccumulative and Toxic) or on the same chemical group (e.g. dioxins). Secondly, the oxidation state of chromium and arsenic emissions to air is missing in EXIOBASE, whereas it very often influences the fate and the effect of the chemical and, subsequently, the impact quantification (regarding human toxicity and ecotoxicity). The "unspecified" CF was therefore assigned to chromium, as available in EF2017, whereas the highest CF was selected regarding arsenic (no "unspecified" CF in that case, but CFs relative to arsenic III and arsenic V). Finally, all the aggregated flows from EXIOBASE needed the calculation of a CF encompassing all the substances included in the aggregation. Each of these CFs was estimated either i) as a weighted average considering the number of emissions or resource produced at EU-27 or at global level, as the preferred solution when feasible, or ii) as an arithmetic average of the CFs available in EF2017 for the flows included in the group.

Overall, considering each impact category, a limited number of elementary flows is considered for the impact assessment step compared to the total number of flows for which a CF is available in the EF-method. In particular, toxic and ecotoxic impacts are calculated considering 11 to 15 substances, compared to 1321 to 7566 substances characterized in the EF-method. Substances in EXIOBASE assigned with a CF considering human toxicity (cancer and non-cancer) and freshwater ecotoxicity are almost entirely emissions to air, whereas emissions to soil and water represent a share comparable to emissions to air in EF-method. Similarly, non-toxic impacts are calculated with considering from 2 to 5 elementary flows, compared to 7 to 212 substances differentiated in the EF-method. Finally, similar observations can be made regarding resource use (e.g., 13 resource flows assigned with a CF in EXIOBASE with respect to minerals and metals resource use, compared to 48 for which a CF is available in EF-method). This lower number of substances characterized (and therefore contributing to impacts in the assessment) using EXIOBASE compared to the full set of substances available in EF-method is essentially due to the absence of the corresponding substances in the EXIOBASE environmental extensions. The aggregation of some elementary flows in EXIOBASE (e.g., "other industrial minerals") also additionally contributes to this discrepancy in the number of substances characterized. On the contrary, six elementary flows calculated from EXIOBASE have been unmapped (that is, these substances have been excluded from the impact characterization) in the absence of the corresponding flows (or proxy flows) in the EF-method.

A shortcoming of the EXIOBASE is that the end years of the real data in the extension tables vary and are therefore not completely up to date. It means that the extension tables are based on real data till a certain year and then the extension coefficients (i.e., the environmental impact per monetary unit of sectoral output) are kept constant. This means that, after the data series based on real data end, the footprint calculations only capture changes in environmental impacts due to changes in output volumes. Changes in environmental efficiency per unit of output are not captured. The end years of the extension tables are: 2015 for energy, 2019 all greenhouse gases (nonfuel, non-carbon dioxide are nowcasted from 2018), 2013 for material use, and 2011 for most others, land, and water.

The **Eurostat Air Emissions Accounts (AEA) by NACE Rev. 2 activity** include air pollutants and greenhouse gases per sector per geographical area from 1995 till, currently (last update 20/12/2023), 2022. The database contains carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), nitrogen trifluoride and sulphur hexafluoride (NF_3 and SF_6), carbon dioxide from biomass used as fuel, sulphur oxides (SO_X), ammonia (NH_3), nitrogen oxides (NO_X), carbon monoxide (CO), particulates (both PM2.5 and PM10), and non-methane volatile organic compounds (NMVOC). In addition, this database provides aggregated air emissions like greenhouse gases[32], acidifying gases[33], and ozone precursors[34].

The data is disaggregated into the NACE Rev. 2 sector classification using 64 branches of activities (A64) and some aggregated values plus direct impacts by activities of households (disaggregated into heating/cooling activities, transport activities, and other activities by households). The disaggregation in geographical areas is available for the individual 27 EU Member States and Iceland, Norway, Switzerland, Serbia, and Turkey. Note, that the dataset is incomplete due to missing data and unavailable data for non-EU countries. For this reason, only the air pollutants for which the AEA data can be supplemented with the EXIOBASE data are retained (total CO_2, CH_4, N_2O, HFC, PFC, NH_3, NO_X, CO, PM2.5, PM10, and NMVOC). This results in the addition of new extension lines for these air pollutants, where EXIOBASE data is used to fill in missing values in the AEA data (AEA-adjusted extension lines).

As a result of the not-updated data in EXIOBASE and the incomplete data (missing values and no complete coverage of all geographical areas) for the Eurostat Air Emissions Accounts, we apply checks and corrections based on external data.

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[32] Greenhouse gas emissions include CO_2, N_2O, CH_4, HFC, PFDC, SF_6 and NF_3, all in CO_2-equivalents.

[33] Acidifying gases include SO_X, NO_X and NH_3, all in SO_2-equivalents.

[34] Ozone precursors include NMVOC, NOX, CO and CH4, all in NMVOC-equivalents.

Table A 22. Data download for environmental extensions

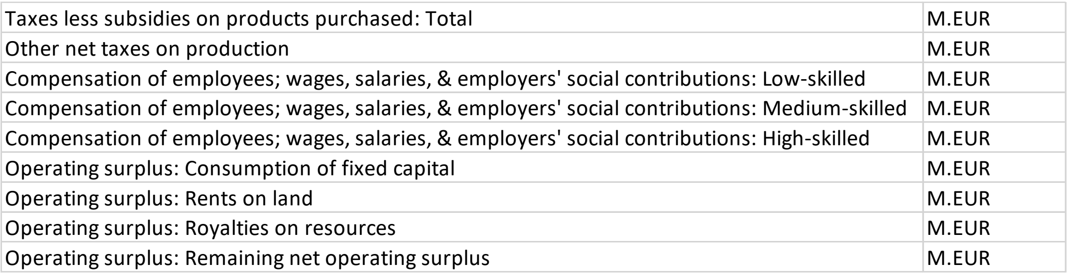
Name	Data provider	Type	Last update	Unit
Air Emissions Accounts Matrix (Gg)	FIGAROe3 by JRC	CSV-file	27/02/2024	Gg
F and Fhh from the file IOT_2015_ixi.zip\satellite	EXIOBASE v3.8.2 by Stadler et al. (2021)[35]	txt-file	21/10/2021	See IOT_2015_ixi.zip\satellite\unit.txt
Air emissions accounts by NACE Rev. 2 activity	Eurostat [env_ac_ainah_r2],	CSV-file	20/12/2023	Tonne (note that some indicators are provided in equivalents)

Source: JRC elaborations

10.2 Extension tables – Financial costs

The extension tables of FIGAROe3 show the generation of value added per sector, disaggregated into 9 categories.

Figure A 3. Details on the gross value added extension table



Taxes less subsidies on products purchased: Total	M.EUR
Other net taxes on production	M.EUR
Compensation of employees; wages, salaries, & employers' social contributions: Low-skilled	M.EUR
Compensation of employees; wages, salaries, & employers' social contributions: Medium-skilled	M.EUR
Compensation of employees; wages, salaries, & employers' social contributions: High-skilled	M.EUR
Operating surplus: Consumption of fixed capital	M.EUR
Operating surplus: Rents on land	M.EUR
Operating surplus: Royalties on resources	M.EUR
Operating surplus: Remaining net operating surplus	M.EUR

Source: based on FIGAROe3 (Cazcarro et al., 2025)

10.3 Extension tables – Employment

The extension tables of FIGAROe3 show two methods for skills: based on education and based on occupation. For each method, the data is disaggregated across male and female and across low-medium-high skilled. The unit is in 1,000 persons.

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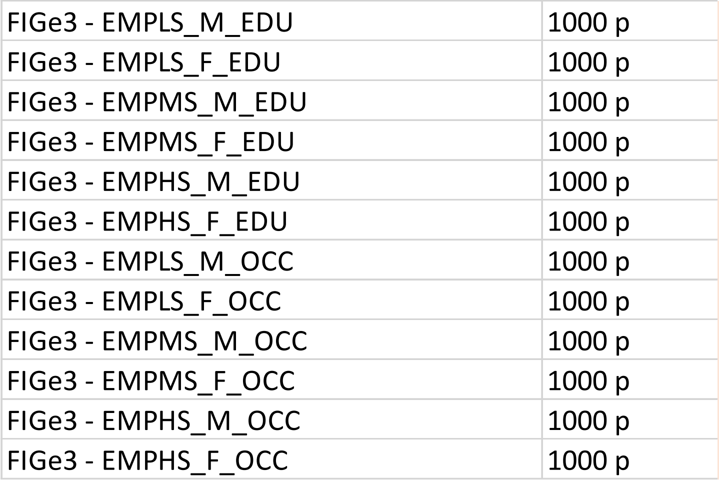
[35] Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., … Tukker, A. (2021). EXIOBASE 3 (3.8.2) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.5589597

Figure A 4. Details on the employment extension table



FIGe3 - EMPLS_M_EDU	1000 p
FIGe3 - EMPLS_F_EDU	1000 p
FIGe3 - EMPMS_M_EDU	1000 p
FIGe3 - EMPMS_F_EDU	1000 p
FIGe3 - EMPHS_M_EDU	1000 p
FIGe3 - EMPHS_F_EDU	1000 p
FIGe3 - EMPLS_M_OCC	1000 p
FIGe3 - EMPLS_F_OCC	1000 p
FIGe3 - EMPMS_M_OCC	1000 p
FIGe3 - EMPMS_F_OCC	1000 p
FIGe3 - EMPHS_M_OCC	1000 p
FIGe3 - EMPHS_F_OCC	1000 p

Source: based on FIGAROe3 (Cazcarro et al., 2025)

10.4 Extension tables – EU resource dependency

Global demand triggers production chains that rely on access to resources. Extension data on the use of metal ores is disaggregated into 12 categories, as shown in the figure below. These extension data is available from the EXIOBASE extension tables.

Figure A 5. Details on the strategic autonomy extension table

Domestic Extraction Used - Metal Ores - Bauxite and aluminium ores	kt
Domestic Extraction Used - Metal Ores - Copper ores	kt
Domestic Extraction Used - Metal Ores - Gold ores	kt
Domestic Extraction Used - Metal Ores - Iron ores	kt
Domestic Extraction Used - Metal Ores - Lead ores	kt
Domestic Extraction Used - Metal Ores - Nickel ores	kt
Domestic Extraction Used - Metal Ores - Other non-ferrous metal ores	kt
Domestic Extraction Used - Metal Ores - PGM ores	kt
Domestic Extraction Used - Metal Ores - Silver ores	kt
Domestic Extraction Used - Metal Ores - Tin ores	kt
Domestic Extraction Used - Metal Ores - Uranium and thorium ores	kt
Domestic Extraction Used - Metal Ores - Zinc ores	kt

Source: based on EXIOBASE

The extension lines show the amount of (global) metal ores extraction. All the lines available from the EXIOBASE model are included, but indeed not all of them are labelled as strategic. Gold, iron, lead, silver, tin, uranium, and zinc are identified as non-critical and non-strategic in the 2023 CRM-list. So, the focus for strategic autonomy should be on the demand for bauxite/aluminium, copper, nickel, PGM's and other non-ferrous. Unfortunately, no data is available for all individual strategic materials.

Annex 11. Implementation of GECO in prospective tables

From the GECO-database only the Multi-Regional Input-Output tables for the GECO Reference scenario are available. In order to align with the NDC-LTS scenario, multiple data points from GECO are used to adapt the FIGe3 supply and use tables to reflect future changes following the GECO NDC-LTS scenario.

First, the IO tables from GECO (using the reference scenario) are used to project the change (compared to 2015) in growth of value added and final demand across the 31 sectors and final demand categories in GECO. Next, the value added for each sector is aligned with specific data on the value added for the NDC-LTS scenario. This data is available from the main macroeconomic indicators reported in the original publication.

In addition, the changing energy production mix and energy use of the GECO NDC-LTS scenario is implemented into the disaggregated supply and use tables of FIGe3. The production and use of energy in the disaggregated supply and use tables are aligned with the projections in the GECO NDC-LTS scenario. The integration is based upon an intermediate step creating balanced tables (in ktoe) on the supply and use of energy. This balance is building upon the GECO Reference scenario and including the specific data on the GECO NDC-LTS scenario on the production and demand for energy by sector. A similar procedure is followed for the CO_2 combustion and non-combustion emissions and the other air pollutants (CH_4, NH_3, NO_X, $PM_{2.5}$, SO_2, and F-gases).

This alignment is limited to the aggregated EU27 and RoW changes derived from the GECO-results. No country specific results were used.

From these GECO-projections at 31 sector level and final demand, relative changes are derived between the base year (2015) and a future year (e.g., 2050). Relative changes are derived for value added generation, energy use, electricity production, final demand consumption, and emission intensities. All relative changes are derived separately for the EU-27 and the RoW. A cross-table shows the links between the sectors from GECO and the 176 sectors from FIGe3. Both a prospective use and supply table are estimated using these sectoral level relative changes. For example, a growth in the sector of 'crops' from GECO between 2015 and 2050 of 24% in EU-27 and 107% in the RoW is used for the FIGe3 cultivation sectors A01_A-A01_H. The input structure is maintained (so growing a similar pace), but the input energy mix is changing according to the relative changes in the energy mix. For example, for the same crop sector the input of coal and oil is reduced by 73% and 43% and substituted by gas in the EU-27.

To balance the prospective supply table with the updated use table, a RAS-method is applied to the supply table.

The change in the extension tables is based on the relative change in the emission intensity. The emission intensity is calculated by dividing the emissions by the value added generated by the sector. The change ratio, often a reduction between 2015 and 2050, is applied to the original emission intensities (for CO_2, CH_4, NH_3, NO_X, $PM_{2.5}$, SO_2, and F-gases). All indicators keep the original intensities in the prospective tables.

Annex 12. Results of all impact categories of IO analysis

Table A 23. Socio-economic and environmental impacts on European Demand of Baseline scenario (BSL 50) and Ambitious Circular Economy scenario (ACE50)

Indicator	ExtensionLine	Unit	STQ20	BSL50	ACE50	STQ20 to BSL50	BSL50 to ACE50	Absolute value
Employment	FIGe3 - EMPLS_M_EDU	1000 p	3.86E+04	5.64E+04	5.64E+04	46.31%	-0.07%	-3.94E+01
Employment	FIGe3 - EMPLS_F_EDU	1000 p	2.68E+04	4.12E+04	4.12E+04	53.45%	0.04%	1.67E+01
Employment	FIGe3 - EMPMS_M_EDU	1000 p	8.67E+04	1.28E+05	1.28E+05	47.69%	-0.08%	-1.01E+02
Employment	FIGe3 - EMPMS_F_EDU	1000 p	5.94E+04	9.28E+04	9.28E+04	56.06%	0.02%	1.61E+01
Employment	FIGe3 - EMPHS_M_EDU	1000 p	3.73E+04	5.83E+04	5.83E+04	56.51%	-0.08%	-4.47E+01
Employment	FIGe3 - EMPHS_F_EDU	1000 p	3.24E+04	5.32E+04	5.32E+04	64.05%	-0.03%	-1.71E+01
Employment	FIGe3 - EMPLS_M_OCC	1000 p	2.96E+04	4.25E+04	4.25E+04	43.74%	0.02%	6.83E+00
Employment	FIGe3 - EMPLS_F_OCC	1000 p	2.15E+04	3.24E+04	3.24E+04	51.11%	0.06%	1.94E+01
Employment	FIGe3 - EMPMS_M_OCC	1000 p	8.91E+04	1.32E+05	1.32E+05	48.13%	-0.09%	-1.23E+02
Employment	FIGe3 - EMPMS_F_OCC	1000 p	5.77E+04	9.00E+04	9.00E+04	55.84%	0.02%	2.10E+01
Employment	FIGe3 - EMPHS_M_OCC	1000 p	4.38E+04	6.83E+04	6.82E+04	55.75%	-0.10%	-6.58E+01
Employment	FIGe3 - EMPHS_F_OCC	1000 p	3.95E+04	6.48E+04	6.48E+04	63.84%	-0.04%	-2.53E+01

Value added	Taxes less subsidies on products purchased: Total	M.EUR	5.67E+05	8.50E+05	8.49E+05	49.82%	-0.11%	-9.64E+02
Value added	Other net taxes on production	M.EUR	2.74E+05	4.56E+05	4.56E+05	66.59%	-0.10%	-4.52E+02
Value added	Compensation of employees; wages, salaries, & employers' social contributions: Low-skilled	M.EUR	4.09E+05	6.60E+05	6.59E+05	61.23%	-0.08%	-5.50E+02
Value added	Compensation of employees; wages, salaries, & employers' social contributions: Medium-skilled	M.EUR	2.62E+06	4.16E+06	4.16E+06	58.92%	-0.15%	-6.10E+03
Value added	Compensation of employees; wages, salaries, & employers' social contributions: High-skilled	M.EUR	3.07E+06	5.01E+06	5.01E+06	63.16%	-0.07%	-3.67E+03
Value added	Operating surplus: Consumption of fixed capital	M.EUR	1.85E+06	2.98E+06	2.97E+06	60.95%	-0.14%	-4.13E+03
Value added	Operating surplus: Rents on land	M.EUR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Value added	Operating surplus: Royalties on resources	M.EUR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Value added	Operating surplus: Remaining net operating surplus	M.EUR	2.94E+06	4.63E+06	4.63E+06	57.82%	-0.143%	-6.62E+03
Resource dependency	Domestic Extraction Used - Metal Ores - Bauxite and aluminium ores	kt	1.14E+04	1.31E+04	1.31E+04	14.78%	0.059%	7.67E+00
Resource dependency	Domestic Extraction Used - Metal Ores - Copper ores	kt	1.36E+05	1.21E+05	1.21E+05	-10.39%	-0.457%	-5.55E+02

Resource dependency	Domestic Extraction Used - Metal Ores - Gold ores	kt	1.24E+03	1.66E+03	1.64E+03	33.92%	-1.115%	-1.85E+01
Resource dependency	Domestic Extraction Used - Metal Ores - Iron ores	kt	6.80E+04	8.67E+04	8.67E+04	27.52%	0.021%	1.84E+01
Resource dependency	Domestic Extraction Used - Metal Ores - Lead ores	kt	4.06E+03	4.62E+03	4.60E+03	13.86%	-0.346%	-1.60E+01
Resource dependency	Domestic Extraction Used - Metal Ores - Nickel ores	kt	8.87E+03	1.08E+04	1.08E+04	22.16%	-0.072%	-7.79E+00
Resource dependency	Domestic Extraction Used - Metal Ores - Other non-ferrous metal ores	kt	5.54E+03	6.82E+03	6.81E+03	22.96%	-0.058%	-3.97E+00
Resource dependency	Domestic Extraction Used - Metal Ores - PGM ores	kt	1.83E+01	1.75E+01	1.74E+01	-4.55%	-0.068%	-1.19E-02
Resource dependency	Domestic Extraction Used - Metal Ores - Silver ores	kt	2.68E+03	3.38E+03	3.36E+03	25.72%	-0.483%	-1.63E+01
Resource dependency	Domestic Extraction Used - Metal Ores - Tin ores	kt	8.22E+03	9.25E+03	9.26E+03	12.46%	0.164%	1.52E+01
Resource dependency	Domestic Extraction Used - Metal Ores - Uranium and thorium ores	kt	2.83E+02	5.80E+02	5.74E+02	104.90%	-1.095%	-6.35E+00
Resource dependency	Domestic Extraction Used - Metal Ores - Zinc ores	kt	1.31E+04	1.48E+04	1.48E+04	12.98%	-0.225%	-3.34E+01
Environmental Footprint	Environmental footprint	points	3.80E+08	2.47E+08	2.46E+08	-35.01%	-0.525%	-1.30E+06

Environmental Footprint	Climate change	kg CO2 eq	4.16E+12	1.46E+12	1.41E+12	-64.88%	-3.41%	-4.98E+10
Environmental Footprint	ozone depletion	kg CFC11 eq	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Environmental Footprint	Ionising radiation	kBq U-235 eq	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Environmental Footprint	photochemical ozone formation	kg NMVOC eq	1.79E+10	1.71E+10	1.71E+10	-4.24%	-0.15%	-2.61E+07
Environmental Footprint	Particulate Matter	disease inc.	1.51E+05	1.52E+05	1.52E+05	0.90%	-0.03%	-5.28E+01
Environmental Footprint	Human toxicity, non-cancer	CTUh	1.01E+05	1.31E+05	1.31E+05	30.08%	0.05%	6.03E+01
Environmental Footprint	Human toxicity, cancer	CTUh	3.23E+03	4.02E+03	4.02E+03	24.14%	0.08%	3.02E+00
Environmental Footprint	Acidification	mol H+ eq	2.95E+10	1.58E+10	1.58E+10	-46.22%	0.00%	-9.93E+04
Environmental Footprint	Eutrophication, freshwater	kg P eq	9.10E+07	1.21E+08	1.21E+08	33.30%	0.03%	3.44E+04
Environmental Footprint	Eutrophication, marine	kg N eq	3.92E+09	2.14E+09	2.13E+09	-45.47%	-0.19%	-4.03E+06
Environmental Footprint	Eutrophication, terrestrial	mol N eq	1.06E+11	5.26E+10	5.25E+10	-50.27%	-0.03%	-1.75E+07

Environmental Footprint	Ecotoxicity, freshwater	CTUe	1.46E+12	1.33E+12	1.33E+12	-8.98%	0.03%	3.61E+08
Environmental Footprint	Land use	Pt	2.38E+14	3.54E+14	3.57E+14	48.95%	0.84%	2.97E+12
Environmental Footprint	Water use	m3 depriv.	2.11E+12	2.99E+12	2.99E+12	41.65%	0.00%	1.39E+08
Environmental Footprint	Resource use, fossils	MJ	7.35E+13	3.27E+13	3.26E+13	-55.46%	-0.32%	-1.05E+11
Environmental Footprint	Resource use, minerals and metals	kg Sb eq	5.43E+06	5.85E+06	5.82E+06	7.73%	-0.55%	-3.21E+04

Note: STQ20 stands for the Status quo scenario and is provided as a reference value

Source: Own calculations

Table A 24. Socio-economic and environmental impacts on global Demand of Baseline scenario (BSL 50) and Ambitious Circular Economy scenario (ACE50)

Indicator	ExtensionLine	Unit	STQ20	BSL50	ACE50	STQ20 to BSL50	BSL50 to ACE50	Absolute value
Employment	FIGe3 - EMPLS_M_EDU	1000 p	4.71E+05	1.09E+06	1.09E+06	131.65%	-0.01%	-8.01E+01
Employment	FIGe3 - EMPLS_F_EDU	1000 p	3.25E+05	7.41E+05	7.41E+05	127.99%	0.00%	-2.23E+01
Employment	FIGe3 - EMPMS_M_EDU	1000 p	9.11E+05	2.09E+06	2.09E+06	129.73%	-0.01%	-2.27E+02
Employment	FIGe3 - EMPMS_F_EDU	1000 p	5.64E+05	1.29E+06	1.29E+06	128.47%	0.00%	-5.05E+01
Employment	FIGe3 - EMPHS_M_EDU	1000 p	3.77E+05	8.33E+05	8.33E+05	120.82%	-0.01%	-1.25E+02
Employment	FIGe3 - EMPHS_F_EDU	1000 p	3.20E+05	6.96E+05	6.96E+05	117.86%	-0.01%	-5.18E+01
Employment	FIGe3 - EMPLS_M_OCC	1000 p	4.62E+05	1.08E+06	1.08E+06	132.85%	0.00%	-2.22E+01
Employment	FIGe3 - EMPLS_F_OCC	1000 p	3.19E+05	7.30E+05	7.30E+05	129.02%	0.00%	-1.53E+01
Employment	FIGe3 - EMPMS_M_OCC	1000 p	9.13E+05	2.10E+06	2.10E+06	129.69%	-0.01%	-2.67E+02
Employment	FIGe3 - EMPMS_F_OCC	1000 p	5.62E+05	1.28E+06	1.28E+06	128.65%	0.00%	-5.33E+01
Employment	FIGe3 - EMPHS_M_OCC	1000 p	3.84E+05	8.43E+05	8.43E+05	119.68%	-0.02%	-1.55E+02
Employment	FIGe3 - EMPHS_F_OCC	1000 p	3.28E+05	7.12E+05	7.12E+05	116.81%	-0.01%	-7.69E+01
Value added	Taxes less subsidies on products purchased: Total	M.EUR	4.44E+06	9.41E+06	9.41E+06	111.88%	-0.02%	-1.59E+03

Value added	Other net taxes on production	M.EUR	2.24E+06	4.86E+06	4.86E+06	116.53%	-0.02%	-7.87E+02
Value added	Compensation of employees; wages, salaries, & employers' social contributions: Low-skilled	M.EUR	2.60E+06	5.55E+06	5.55E+06	113.65%	-0.02%	-1.09E+03
Value added	Compensation of employees; wages, salaries, & employers' social contributions: Medium-skilled	M.EUR	1.76E+07	3.81E+07	3.81E+07	116.26%	-0.03%	-9.81E+03
Value added	Compensation of employees; wages, salaries, & employers' social contributions: High-skilled	M.EUR	1.48E+07	3.15E+07	3.15E+07	112.52%	-0.02%	-6.50E+03
Value added	Operating surplus: Consumption of fixed capital	M.EUR	1.09E+07	2.35E+07	2.34E+07	115.29%	-0.02%	-5.76E+03
Value added	Operating surplus: Rents on land	M.EUR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Value added	Operating surplus: Royalties on resources	M.EUR	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Value added	Operating surplus: Remaining net operating surplus	M.EUR	1.51E+07	3.25E+07	3.25E+07	115.44%	-0.03%	-1.04E+04
Resource dependency	Domestic Extraction Used - Metal Ores - Bauxite and aluminium ores	kt	2.62E+05	7.05E+05	7.05E+05	168.97%	0.05%	3.46E+02
Resource dependency	Domestic Extraction Used - Metal Ores - Copper ores	kt	1.26E+06	3.22E+06	3.23E+06	155.07%	0.01%	4.36E+02
Resource dependency	Domestic Extraction Used - Metal Ores - Gold ores	kt	1.66E+04	4.26E+04	4.26E+04	156.91%	-0.03%	-1.44E+01

Resource dependency	Domestic Extraction Used - Metal Ores - Iron ores	kt	1.32E+06	3.09E+06	3.09E+06	133.53%	0.01%	4.31E+02
Resource dependency	Domestic Extraction Used - Metal Ores - Lead ores	kt	6.98E+04	1.95E+05	1.95E+05	179.17%	0.00%	6.69E+00
Resource dependency	Domestic Extraction Used - Metal Ores - Nickel ores	kt	3.56E+05	6.44E+05	6.44E+05	80.79%	0.00%	-2.93E+01
Resource dependency	Domestic Extraction Used - Metal Ores - Other non-ferrous metal ores	kt	1.37E+05	2.71E+05	2.71E+05	98.55%	0.00%	-1.27E+01
Resource dependency	Domestic Extraction Used - Metal Ores - PGM ores	kt	3.47E+02	8.07E+02	8.07E+02	132.29%	0.01%	4.49E-02
Resource dependency	Domestic Extraction Used - Metal Ores - Silver ores	kt	2.02E+04	5.40E+04	5.40E+04	167.87%	-0.06%	-3.00E+01
Resource dependency	Domestic Extraction Used - Metal Ores - Tin ores	kt	3.29E+05	8.59E+05	8.59E+05	161.41%	0.00%	-1.99E+01
Resource dependency	Domestic Extraction Used - Metal Ores - Uranium and thorium ores	kt	2.52E+03	5.45E+03	5.44E+03	116.03%	-0.12%	-6.77E+00
Resource dependency	Domestic Extraction Used - Metal Ores - Zinc ores	kt	2.20E+05	6.93E+05	6.93E+05	215.83%	0.01%	3.75E+01
Environmental Footprint	Environmental footprint	points	4.79E+09	5.94E+09	5.94E+09	23.96%	-0.03%	-1.53E+06
Environmental Footprint	Climate change	kg CO2 eq	4.18E+13	2.69E+13	2.68E+13	-35.67%	-0.19%	-5.22E+10

Environmental Footprint	ozone depletion	kg CFC11 eq	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Environmental Footprint	Ionising radiation	kBq U-235 eq	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Environmental Footprint	photochemical ozone formation	kg NMVOC eq	1.62E+11	2.22E+11	2.22E+11	36.74%	-0.01%	-3.24E+07
Environmental Footprint	Particulate Matter	disease inc.	2.11E+06	3.20E+06	3.20E+06	51.78%	0.00%	-5.27E+01
Environmental Footprint	Human toxicity, non-cancer	CTUh	1.15E+06	2.41E+06	2.41E+06	109.61%	-0.03%	-6.53E+02
Environmental Footprint	Human toxicity, cancer	CTUh	4.01E+04	8.56E+04	8.56E+04	113.42%	-0.05%	-4.49E+01
Environmental Footprint	Acidification	mol H+ eq	3.76E+11	3.21E+11	3.21E+11	-14.53%	0.00%	1.13E+07
Environmental Footprint	Eutrophication, freshwater	kg P eq	1.81E+09	3.97E+09	3.97E+09	119.37%	0.00%	-3.49E+04
Environmental Footprint	Eutrophication, marine	kg N eq	3.81E+10	2.82E+10	2.82E+10	-25.97%	-0.01%	-2.96E+06
Environmental Footprint	Eutrophication, terrestrial	mol N eq	1.28E+12	9.66E+11	9.66E+11	-24.44%	0.00%	-1.61E+07
Environmental Footprint	Ecotoxicity, freshwater	CTUe	1.59E+13	2.13E+13	2.13E+13	33.97%	0.01%	1.07E+09

Environmental Footprint	Land use	Pt	4.73E+15	1.17E+16	1.17E+16	147.05%	0.00%	4.11E+11
Environmental Footprint	Water use	m3 depriv.	3.59E+13	8.16E+13	8.16E+13	127.25%	0.00%	-2.59E+09
Environmental Footprint	Resource use, fossils	MJ	1.01E+15	1.01E+15	1.01E+15	0.18%	-0.01%	-7.30E+10
Environmental Footprint	Resource use, minerals and metals	kg Sb eq	9.57E+07	2.48E+08	2.48E+08	159.41%	-0.01%	-1.27E+04

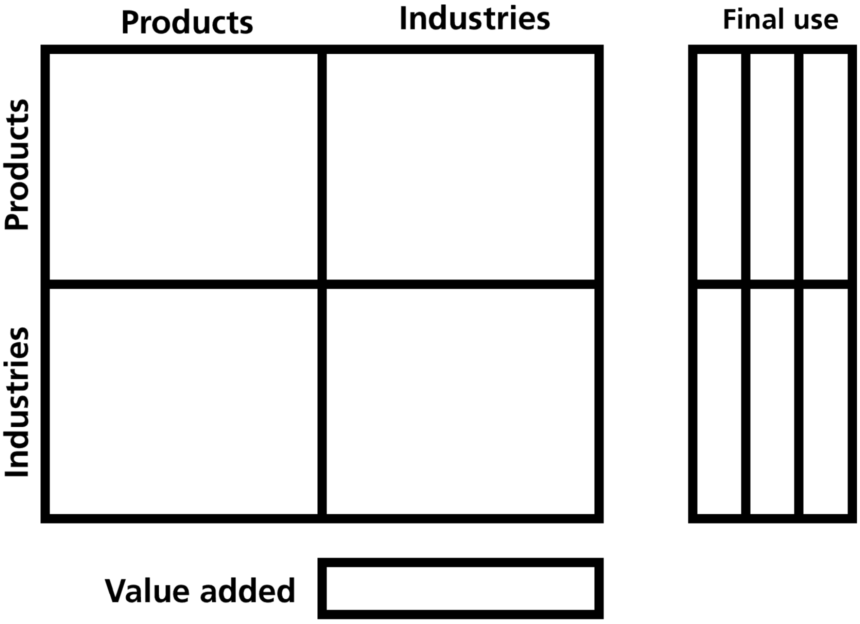
Note: STQ20 stands for the Status quo scenario and is provided as a reference value

Source: JRC calculations

Annex 13. Description of FIDELIO 4 modules

Static supply-use model: The first module is a static supply-use model. It allows an assessment of intersectoral spillovers along global supply chains, following a standard Leontief approach that links the demand side of the model with the production side. The outline of the SUT structure is shown in **Figure A 6**.

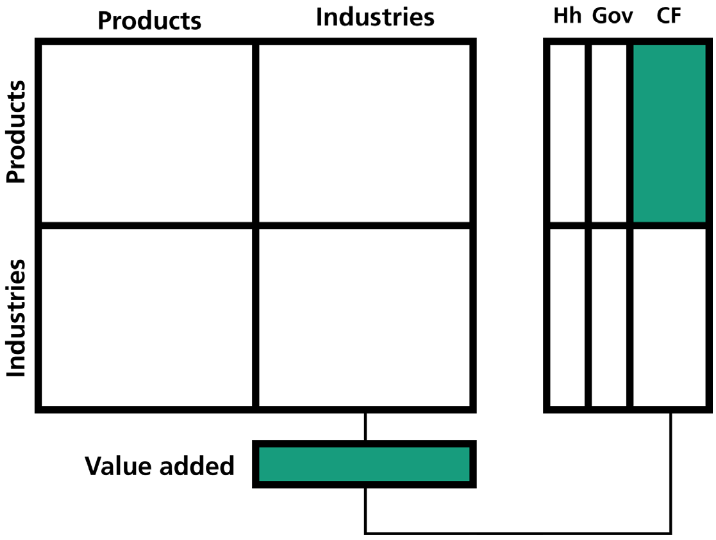
Figure A 6. First module of FIDELO: Static Supply-module



Source: JRC illustration

Investment dynamics: The second module captures investment dynamics by expanding the gross fixed capital formation column (GFCF) into an investment matrix by industry and product. For example, an investment by German car manufacturers will be spent for about 70% in research and development services and for about 30% in other services or goods. An investment in this industry will therefore primarily have an impact on R&D and its value chain. Investment dynamics are added, linking, for example, total output and gross operating surplus in the value-added section of the SUT to the in-vestment decisions of an industry. Capital accumulation is added by adding investment and subtracting depreciation over time. Comparing the results of the investment module with those of the supply-use module makes it possible to assess the spill-over effects of investment in other sectors, such as R&D. The extension of the investment matrix and the dynamics are shown in the stylized version of an investment extended SUT structure in **Figure A 7**.

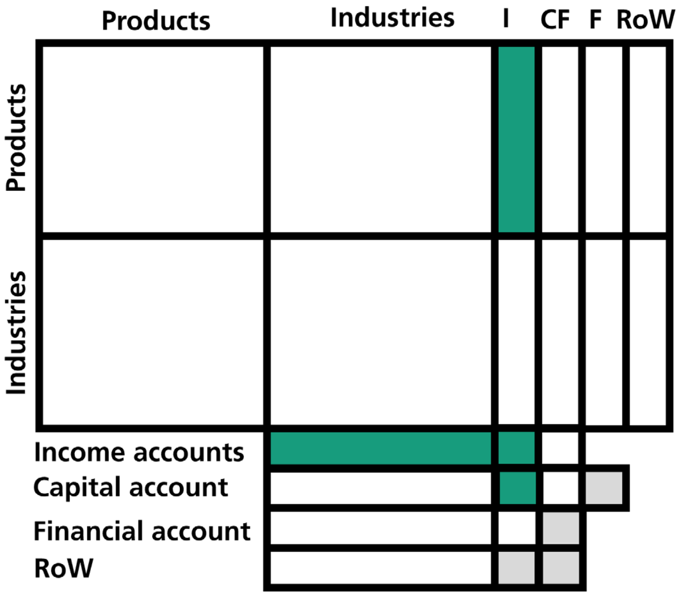
Figure A 7. Second module of FIDELIO: Investment dynamics



Source: JRC illustration

Consumption dynamics: The third module adds consumption dynamics. For this purpose, the table is restructured into a national accounting matrix (NAM), a format of IO data mainly used for computable general equilibrium models for a representation of the circular flow of income and is displayed in **Figure A 8**. Household consumption is divided into quintiles, allowing the impact on different parts of the income spectrum to be assessed. Changes in household disposable income lead to changes in household expenditure based on an econometrically derived Almost Ideal Demand System (AIDS). Using the NAM structure, dynamics such as the link between wages and household disposable income or taxes and government spending are added. The module allows for an assessment of income effects highlighting the income distribution as well as CE rebounds due to re-spending.

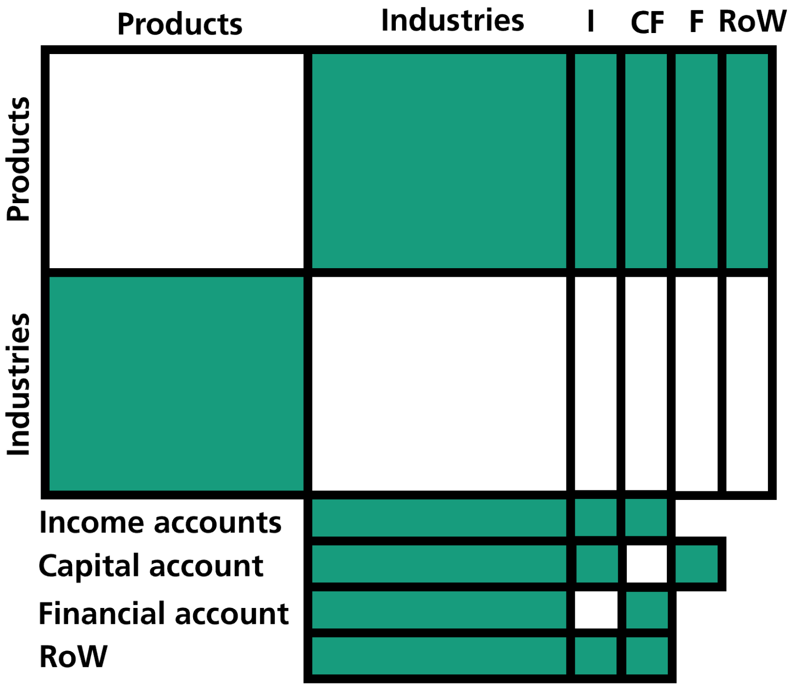
Figure A 8. Third module of FIDELIO: Consumption dynamics



Source: JRC illustration

Full model: In the full model, consumer and producer prices, wages and interest rates are activated. A nested constant elasticity of substitution function is now active on the supply side of the model using a standard CGE approach. While in the other modules the production recipes were kept static, in the fourth module changes in production inputs are possible when their prices change relative to each other. The demand for imports is decided on the basis of an Armington elasticity, which takes into account price differences between countries. In the model, exports mirror changes in the demand for imports. Changes in consumer prices can lead to changes in consumption and vice versa. Thereby, a fall in demand can lead to a fall in prices, resulting in a partial increase in demand. This is a price rebound and can be investigated using the full model as opposed to the third module. To enhance realism, FIDELIO incorporates price rigidities, acknowledging that industries and consumers require time to adjust to optimal production and consumption levels. Economic equilibrium is achieved only in the long run, reflecting a neo-Keynesian approach that is more realistic than assuming an immediate adjustment to optimal decisions. The price dynamics will influence all matrices of the model as displayed in.

Figure A 9. Fourth module of FIDELIO: Full model with price dynamics



Source: JRC illustration

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